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DISTRIBUTION NETWORK RELIABILITY

by

© HUNG KWENG KUA

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF ELECTRICAL ENGINEERING

EDMONTON, ALBERTA
SPRING 1986

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled DISTRIBUTION NETWORK RELIABILITY submitted by HUNG KWENG KUA, in partial fulfilment of the requirements for the degree of Master of Science in Electrical Engineering.

Don Koval
Supervisor

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External Examiner

Date: March 20. 19.86.

ABSTRACT

The objective of an electrical utility is to supply electrical energy and to provide a high degree of service reliability to their industrial, residential and commercial consumers as economically as they possibly can. Their consumers expect a high level of service reliability to operate their electrical and electronic appliances and and systems. However, when part of a power system fails, there is a possibility that electrical services may be curtailed. A long term interruption of electrical service can have a significant impact on society (e.g., the 1977 New York City Blackouts.) For this reason, reliability is one of the major factors affecting the planning, operation, and maintenance activities of any power system network.

The methodology for quantitatively evaluating the reliability levels of individual consumers being serviced by a power system network is a complex problem. Power system network reliability is defined as the probability that the network configuration will successfully perform its intended function of supplying energy to its consumers on a continuous basis under all operating and environmental conditions. The research presented in this thesis is directed at modelling and simulating the reliability performance of actual complex power system networks. This thesis describes a flow graph method for identifying and simulating the initial operational paths of a given network configuration, and evaluating individual consumer reliability levels within any power system network configuration. The calculations involve evaluating the probabilities, frequencies of occurrence and durations of system failure and restoration states. The impact of normal and adverse weather patterns and power system disturbances which can significantly affect service reliability levels are also considered in this thesis. The reliability performance of an actual distribution network, i.e., the University of Alberta's power system distribution network is studied and discussed in some detail.

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CHAPTER I

INTRODUCTION

A distribution system is defined as those parts (i.e., primary and secondary electrical equipment) of an electric utility which link the transmission and generation subsystems to individual consumer service entrances. Distribution primary and secondary networks deliver electrical energy from the generation stations and/or transmission grids, or substations via distribution primary feeder circuits or networks to the individual consumer transformer locations, where the primary feeder or network voltage is transformed to the individual customer's utilization voltage (e.g., 120/240V). Distribution primary networks and feeder circuits operate at many voltage levels (e.g., 4.16kV, 12.47kV, 13.8kV, 25kV, 60kV, etc.). The magnitude of primary voltage level and the density of consumer loads within a given network configuration has a significant impact on the design of distribution network configuration (i.e., whether it will be operated radially, looped or as a network) [1].

1.1 Distribution Networks

A distribution network is basically divided into three parts:

(i) the subtransmission circuits and distribution substations;

(ii) the primary distribution circuits;

(iii) the distribution transformers and secondary circuits.

A schematic diagram of a distribution network configuration is shown in Figure 1.1 [1].

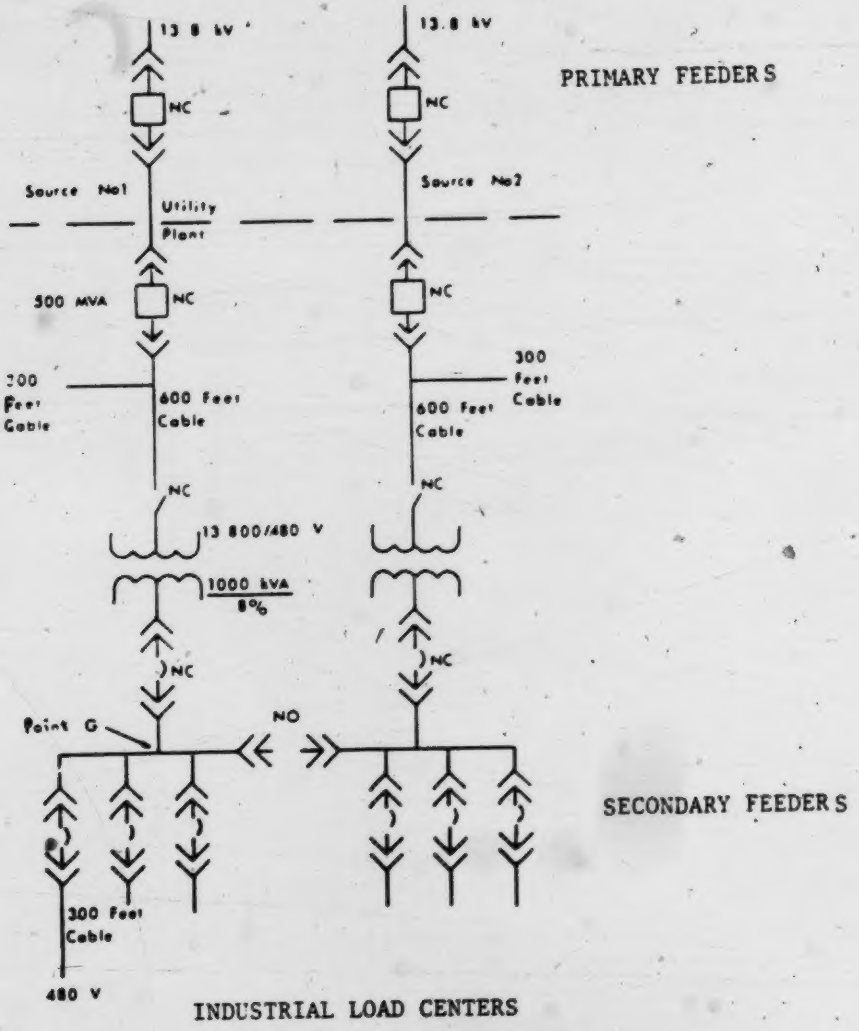

13.8 kV
13.8 kV
PRIMARY FEEDERS
NC
NC
Source No1
Source No2
Utility
Plant
500 MVA
NC
NC
300 Feet Cable
600 Feet Cable
600 Feet Cable
300 Feet Cable
NC
NC
13 800/480 V
1000 kVA
8%
NC
NC
NO
Point G
SECONDARY FEEDERS
300 Feet Cable
480 V
INDUSTRIAL LOAD CENTERS

Figure 1.1 Distribution industrial network configuration.

The distribution circuit configuration depends upon the location and magnitude of the individual consumer's load (i.e., the circuit's load density). The classical distribution system configurations are the radial, open-loop, and grid configuration with combinations and modifications of these arrangements. The primary system includes the distribution network between the substation and all of the consumers distribution transformers serving them, while the secondary system consists of the distribution transformers and the secondary service lines or cables feeding the consumer's load center as shown in Figure 1.1 [1].

A distribution network configuration consists of many individual components (e.g., links) which are interconnected in various ways to serve all the customers in a given geographical area. The objective of a particular distribution network configuration is to link various generations nodes and/or substations nodes with numerous load centers forming a distinctive set of operational paths. However, when one or more individual components fails or are removed from service for maintenance or new components added to the distribution network, a new set of operational paths is created. One of the difficulties in practice is to manually identify the new paths for a large distribution network. However, given a knowledge of the old and new operational paths, continuity of service or flow to critical consumer load points located within the distribution network can be validated and ensured.

The fundamental objectives of any network configuration and its associated operating practices are to satisfy consumer or load requirements as economically as possible and provide a reasonable assurance of quality and continuity of service. A knowledge of individual load or consumer service reliability levels is an extremely important factor in the design which affects the operating characteristics of the network and the consumer's electronic and electrical systems. Several papers [2-7] have been published containing algorithms for calculating the reliability of a general network configuration. These reliability techniques are complicated, time consuming and involve many approximations and assumptions. Other techniques simply evaluate the overall network reliability levels with very little attention being directed towards evaluating individual consumer or load point levels of reliability. However, from a consumer's viewpoint his location within the network configuration has a significant impact on the level of service reliability levels he/she receives.

1.2 Reliability Techniques

New reliability evaluation techniques for large power systems have recently received considerable attention in the literature, however, these techniques are not very effective, Billinton [2] indicated that most of the work done to date in the distribution system reliability deals with a Markovian model for the power system being considered.

The concept of conditional probability and the delta-star transformation techniques used for reliability evaluation of non-series, non-parallel systems become extremely complicated for reliability evaluation of a large power system. Another approach using Boolean description for the network was also suggested for power system reliability evaluations [8]. The disadvantage of this technique is that the complexity in the calculations increases with the complexity of the system structure at an increasing rate. Billinton and Singh [9] presented a method using minimal cut-sets for transmission and distribution reliability and failure frequency evaluation. The cut-set approach can be applied to a simple network as well as complex network configuration and is a very suitable technique for evaluating the reliability and frequency indices of power system distribution networks.

1.3 Power System Operation

A power system should be designed and expansion facilities planned for so that it can perform its intended function of providing a reasonable assurance of quality and continuity of service to its consumers. The risk of power interruptions can be reduced by introducing redundancies in the transmission and distribution networks. Reliability models provide a means of estimating the frequency and duration of system interruptions and costs of operating various network configurations.

1.4 Thesis Objective

This thesis is directed at modelling and simulating the performance of actual complex power system networks. The computerized path identification model provides the basic knowledge of a network required for many reliability studies (e.g., reliability levels at particular load points.) No bus or node numbers are required by the computer model as input data, only the adjacent connecting elements of each element in the network are necessary. Any modifications to the network (e.g., additions, removals) do not have to be recoded, i.e., the original data remains the same and the modification are handled within the computer program. The computer algorithm presented in the thesis is extremely fast and efficient when compared with manual methods.

1.5 Scope Of Thesis

Chapter II and III illustrate the proposed algorithm and model for tracing the operational paths and evaluating the reliability levels of a given network configuration under normal operating conditions and when components are removed from service. Particular emphasis was placed on the data definition, acquisition and validation stages of the computer model. These stages are the basis of the path tracing algorithm and are illustrated with a standard network configuration. Chapter IV presents the results obtained when the proposed model was applied to an actual distribution system (i.e., The University of Alberta distribution system). The impact of electrical component preventive maintenance activities and temporary outages on the network reliability levels are examined in detail in Chapter V and Chapter VI. Chapter VII presents the conclusions and discussions of the thesis.

CHAPTER II

OPERATIONAL PATHS

2.1 Basic Concepts Of Flow Graph Techniques

A power system network is composed of many electrical components interconnected in various ways to form an operating system, as shown in Figure 2.1, for example.

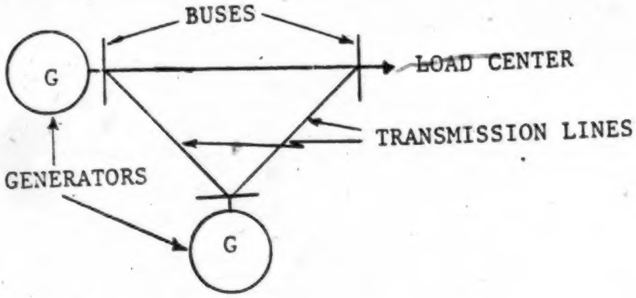


Figure 2.1 A simple power system network.

2.1.1 Manual Algorithm

In the flow graph methodology, it is necessary to establish the number of "possible" interconnections of the parts of the network (i.e., a total of "N" parts) when all possible interconnections (i.e., taken N at a time) have been established. Then, the "presently" operating configuration can be defined. The basic concepts of flow graph method for tracing operational paths can be described in the following steps.

STEP 1 - Numbering The Components

Consider a system with N unidirectional components (i.e., the flow of energy being restricted to flow in one direction only). Note: bidirectional components system will be discussed later in this section. Each component within the system is arbitrarily numbered 1 through N. Note that the order of numbering the components is not important. Only the component number, the direction of flow through a component (unidirectional or bidirectional) and its adjacent connecting components are of importance to the flow graph path tracing method.

STEP 2 - Forming The First Order Combinations

Each component in the network is taken to form a first order combination (i.e., a combination with only one component). A combination is defined as all the possible arrangements of a set of components where the order of the arrangements is not important (e.g., 1-2-3-4 = 1-3-2-4 = 1-4-2-3). A "m-th" order combination is defined as a combination with m components. For a N unidirectional component system there exist $\frac{N!}{(N-1)!\ 1!}$ of these first order combinations.

Example

Consider a four unidirectional components system as shown in Figure 2.2, i.e., N = 4, then there exists $\frac{4!}{(4-1)!\ 1!}$ 4 components of the first order combination and they are:

(1) 1 (2) 2 (3) 3 (4) 4 .

Note: N! = 1 * 2 * 3 * ... * N

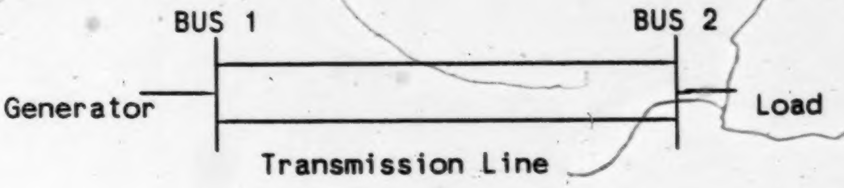


Figure 2.2(a) Simple system to illustrate the flow graph method.

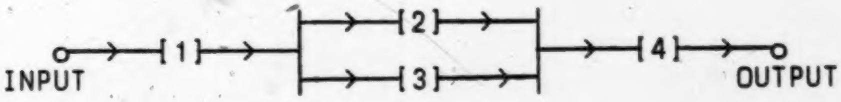


Figure 2.2(b) Block diagram of Figure 2.2(a).

STEP 3 - Forming The Second Order Combinations

Form all the possible second order combinations by connecting any two components at a time and let them form the second order combinations or links (i.e., a two components link). In a N unidirectional system there will be $\frac{N!}{(N-2)!\,2!}$ second order combinations. For the example above, there are six second order combinations

(1) 1-2 (2) 1-3 (3) 1-4 (4) 2-3 (5) 2-4 (6) 3-4

STEP 4 - Forming The Third Order Combinations

Similarly, all the third order combinations are formed by connecting three components at a time at letting them form a three components link. The total number of these third order combinations are given by $\frac{N!}{(N-3)!\,3!}$. For the N = 4 system above, this works out to be 4, i.e., there are four third order combinations for a system with four unidirectional components. The combinations are (1) 1-2-3 (2) 1-2-4 (3) 1-3-4 (4) 2-3-4 .

STEP 5 - Forming The Successive Combinations

The process is repeated until all the possible order of combinations of the components are found. The maximum combination order that can be formed is limited to the total number of components in the system (i.e., N), and the maximum number of a m-th order combinations is given by:

$$\frac{N!}{(N-m)!\ m!} \qquad (1)$$

From the above expression, it is obvious that there exists only one N-th order combination, where all the components appear in the combination.

Therefore, for a 4 component system (i.e., N=4) the maximum order of combination that can be formed is four and there is only one such combination, 1-2-3-4 . The total number of combinations for an N unidirectional component system is then the summation of all the combination orders that can be found for the given system, i.e.,

$$\sum_{m=1}^{N} \frac{N!}{(N-m)!\ m!} = 2^{N} - 1 \qquad (2)$$

where m is the order of combination. The overall combinations for the system in Figure 2.2 are listed in Table 2.1.

Table 2.1 A list of the overall combinations for the four unidirectional component system as shown in Figure 2.2.

Combination set	Components within combination	Order of combination
1	1	1
2	2	1
3	3	1
4	4	1
5	1 2	2
6	1 3	2
7	1 4	2
8	2 3	2
9	2 4	2
10	3 4	2
11	1 2 3	3
12	1 2 4	3
13	1 3 4	3
14	2 3 4	3
15	1 2 3 4	4

STEP 6 - Identifying The Operational Paths

Scan through all the combinations of possible connections to locate those combinations that satisfy the following "path" criteria:

(i) there must be a source (input) component within the combination;

(ii) the desired load (output) component must be contained within the combination;

(iii) all the components present must be able to interconnect with one another to allow a forward flow.

For the 15 combinations of the 4 components system shown in Figure 2.2, there are two combinations that satisfy all the criteria previously listed (i.e., combination #12 and #13). Thus, there are two operational paths for the system in Figure 2.2 and they are paths 1-2-4 and 1-3-4. Since component 1 is a source, component 4 is the load, the flow is from component 1 to component 2, and then from component 2 to component 4, or from component 1 to component 3 and from component 3 to component 4, there is no need to rearrange the components within the combination list to form a logical flow path (i.e., one that originates with a source node and ends with the desired load component).

The same process described for unidirectional components also applies to a bidirectional system, with the exception that the order of arrangement of the components within a a combination is important. If all the components (N) within a network configuration are bidirectional, then there exist a total of $\frac{N!}{(N-m)!}$ of m-th order permutations. Note that this is m! more than the unidirectional system m-th order combinations. The total number of permutations for a N bidirectional component system is also the summation of all the possible order of permutations of the N components, and the maximum order that can be formed is N, the number of components in the network configuration. An example of a bidirectional component system is shown in Appendix A.

2.1.2 Computer Algorithm

The computerized flow graph method may be described as follows:

STEP 1

All the components (elements) in the given network configuration are numbered 1 through N, where N is the total number of components within the given network configuration and the numbering order is not of importance. The component numbers are arranged with the source (input) component number appearing first in the list, and the output component numbers appearing last.

For the simple power system network of Figure 2.2(a), the list for the system components is as follows:

List 1 2 3 4

STEP 2

Each of the component (e.g., component 1) is appended to every components in the list, i.e., forming combination with itself and/or with the other components with higher address (e.g., components 2, 3 and 4) within the given system. This would result in (2^N - 1) combinations.

(i) For the first element, this is rather trivial operation. The resulting combination list for the system in Figure 2.2 is:

Combination list :

*

* 1

where * is as a null component. When a given component is combined with the null item the result is simply that component alone. The null item appears in the list to initiate the process and to insure that the combinations of the N components taken one at a time will appear in the list of combinations.

(ii) The combination list in STEP 2.(i) is appended with the second component of List. Hence continuing with component #2, the following results are obtained for the sample system above:

List 1 2 3 4

Combination list:

*

* 1

....

* 2

new combinations

* 1 2

(iii) Repeat STEP 2.(ii) with the next component in List and the new combination list can be found. The appending process is repeated until all the components in List have been appended. Therefore, continue with component #3:

List 1 2 3 4

Combination list:

* 1

....

* 2

```
            *   1   2
.................................
            *   3
            *   1   3
            *   2   3          new combinations
            *   1   2   3
```

Note that the new combinations of path were formed be appending component #3 to all of the combinations appearing in the list above component #3. Finally, component #4 is considered, the list is then complete and contains all of the possible combinations of these four components taking one at a time until all the four components have been considered. The final list of possible paths is shown below with the null item deleted except for the first element.

```
     List    1   2   3   4
Combination list:
             *
             1
................................
             2
             1   2
................................
             3
             1   3
             2   3
             1   2   3
................................
             4
             1   4

             2   4
```

1 2 4
3 4
1 3 4
2 3 4
1 2 3 4

The procedure previously discussed is applied to a simple flow graph to illustrate the terminology of the flow graph algorithm in indentifying all the paths in the system. This method considers loops in a network configuration, however, loops often form unnecessary paths which are omitted. Consider the flow graph network shown in Figure 2.3. The components of the flow graph are numbered accordingly. It is important that the N components in a system be can arbitrarily numbered 1 through N for the following discussion.

An edge (i.e., a link) leading to the next node further away from the source will be referred to as a forward edge. Edges exhibiting the opposite property will be called reverse edges. Figure 2.3 does not have any reverse edges, and therefore, the system does not contain any loops (i.e., assuming unidirectioal components). Note that the direction of flow is as shown, no reverse flow is allowed. The paths in Figure 2.3 can be systematically generated in the following manner. First, the components must be ordered in a list such that the component closest to the input (source) appear highest in the list (i.e., as described previously in STEP 1). The paths of the network are then generated by forming all the possible combinations of the components.

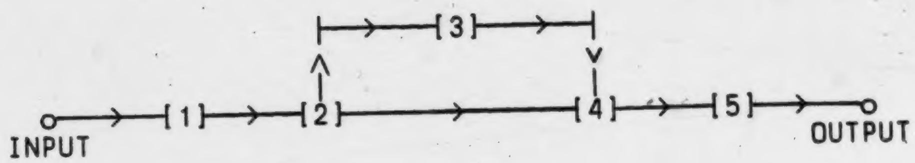


Figure 2.3 Flow graph - flow direction is as shown.

The resulting combinations of all the components 1, 2, 3, 4 and 5 using this technique are listed as follows:

```
List    1    2    3    4    5

      1
      2
      1    2
     ----------
      3
      1    3
      2    3
     ----------
      1    2    3
     ---------------
      4
      1    4
      2    4
     ----------
      1    2    4
     ---------------
      3    4
     ----------
      1    3    4
      2    3    4
     ---------------
      1    2    3    4
     --------------------
      5
      1    5
      2    5
      1    2    5
      3    5
      1    3    5
      2    3    5
      1    2    3    5
```

```
  4   5
---------
  1   4   5
  2   4   5
------------
  1   2   4   5
----------------
  3   4   5
------------
  1   3   4   5
  2   3   4   5
----------------
  1   2   3   4   5
--------------------
```

The combinations listed above that are underlined are the correct combinations of the components, that form logically possible paths for the flow of energy. Those that are not underlined are invalid combinations, i.e., not logically possible paths. These invalid combinations can be simply avoided by never appending a new edge within the system to the combination in the list unless the ending node of the combination in the system matches the starting node of the next edge in the same network configuration.

For the logically possible combinations, underlined, there are some that are incomplete, i.e., they do not start from an input component and end at the specified output component. Therefore, these paths must then be eliminated along with those invalid combination of paths. The elimination of the incomplete combinations can be easily done by simply scanning through the list of combinations, putting a '1' if the path is complete and '0' if it is incomplete, i.e., eliminiating that row. The process is continued until the bottom of the list is reached. Then valid paths are moved up to occupy those invalid paths. The total number of rows in the list will then be the maximum number of paths that can cause a network to operate successfully. For the example above (Figure 2.3) the maximum number of paths for the network success is two, they are:

Path #1 [1 2 3 4 5]

and

Path #2 [1 2 4 5] .

2.2 Initial Data Requirements For The Proposed Model

The network topology of the system to be studied showing the interconnections or links between the various network components or elements or branches is required to identify the system operational paths. The computerized model initially requires the definitions of several terms to understand the basic input requirements for the model. Figure 2.4 is an example of a particular section of a network in which the nodes of the network are numbered (i.e., bus numbers). However, the computer model proposed in the thesis is independent of the node numbers and requires only the element numbers of the physical components contained within the network configuration [10].

The network configuration shown in Figure 2.4 can be redefined in terms of element numbers (i.e., each physical component is identified with a number, known as element number). A junction node or bus (i.e., component terminations) is treated as an element (e.g., element #4) since its failure can have significant impact on the operational paths and the reliability performance of any network configuration.

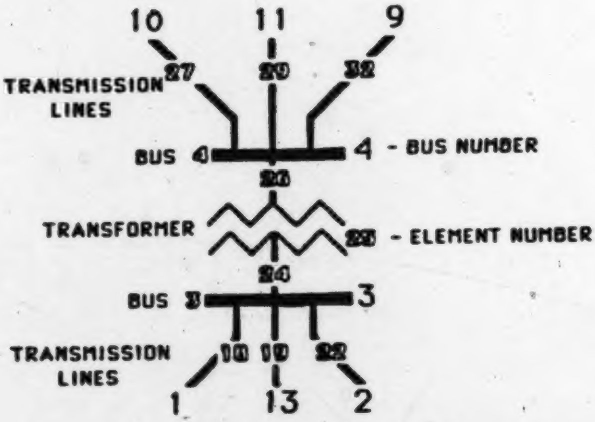

10
11
9
27
29
32
TRANSMISSION LINES
BUS 4
4 - BUS NUMBER
26
TRANSFORMER
25 - ELEMENT NUMBER
24
BUS 3
3
TRANSMISSION LINES
18
19
22
1
13
2

Figure 2.4 Section of an actual network configuration.

The original network diagram (i.e., Figure 2.4) can also be represented as an element block diagram as shown in Figure 2.5 . Each element in the network must be classified to whether it is unidirectional or bidirectional element. This classification is dependent upon the operational characteristics of the element (e.g., power system transmission lines, communication lines, inverters or rectifier circuits in electronics, etc.).

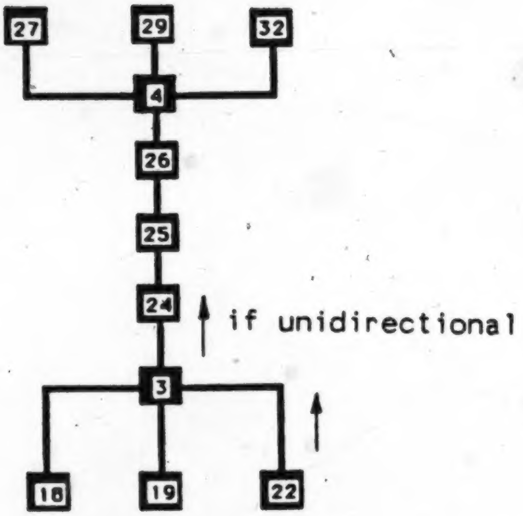


Figure 2.5 Element block diagram of network section.

2.2.1 Adjacent Connecting Element

Each element within a given network configuration may or may not be connected to other elements. The computer algorithm for identifying the operational paths of a given network configuration is based on the identification of the connecting elements associated with a given element in any network configuration and whether the adjacent connecting elements are undirectional or bidirectional. An adjacent connecting element of a given element is defined from the perspective of the given element; i.e., if the "flow" (e.g., power, water, computer data, etc.) originating from the adjacent element can be received by the given element then that adjacent element is considered as an adjacent connecting element. In the case of "unidirectional" elements or paths, the adjacent connecting element may be constrained to allow "flow" to be in one direction only (e.g., reverse power relays) and from the perspective of the given element, the adjacent element will not be considered as a connecting element even through they may be physically connected.

With reference to Figure 2.5, the adjacent connecting elements for some elements in the section of the network are shown in Table 2.2 for various element directional constraints.

Table 2.2 Adjacent connecting elements of the network shown in Figure 2.5.

ELEMENT NUMBER	ADJACENT CONNECTING ELEMENTS	COMMENTS
3	18, 19, 22	element 24 UNIDIRECTIONAL
3	18, 19, 22, 24	If element 24 BIDIRECTIONAL
4	26, 27, 29, 32	element 26 Bidirectional
24	3, 25	element 24 Bidirectional

2.2.2 Source Elements and Load or Consumer Elements

A source element is defined as an element which generates or transmits or computes the content of the "flow" (e.g., water, electrical energy, communication data, etc.) and utilizes the network medium to distribute the "flow" to various load or consumer elements where the "flow" is utilized according to predefined characteristics of the flow process. A load or consumer element is defined as an element which receives a portion of the "flow" from the network configuration.

2.3 Case Study

2.3.1 Formation of ACE(i,j) Array

The methodology associated with the computer path algorithm will be presented and developed on the basis of the network configuration shown in Figure 2.6 The model requires the network topology to be defined in terms of element numbers as shown in Figure 2.7 for the Standard IEEE 14 bus power system. Once the element block diagram of the network is drawn, the adjacent connecting element array (i.e., ACE(i,j)) of the block diagram must be defined. The ACE(j,j) array for the element block diagram shown in Figure 2.7 is shown in Figure 2.8.

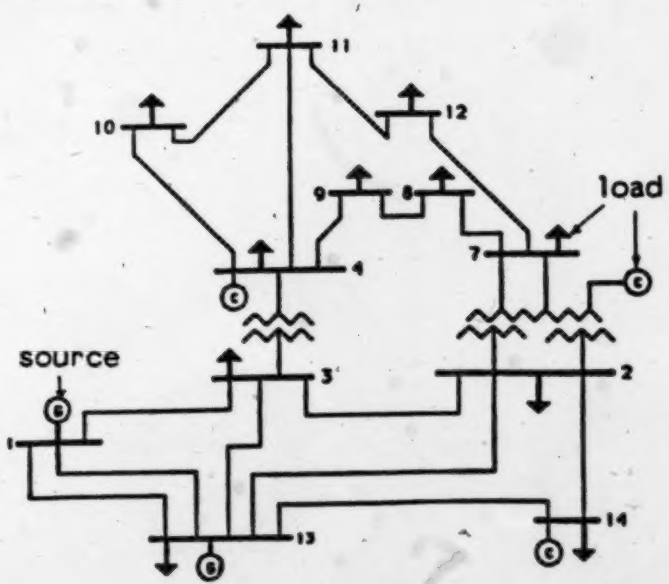


Figure 2.6 Standard IEEE 14 bus power system network.

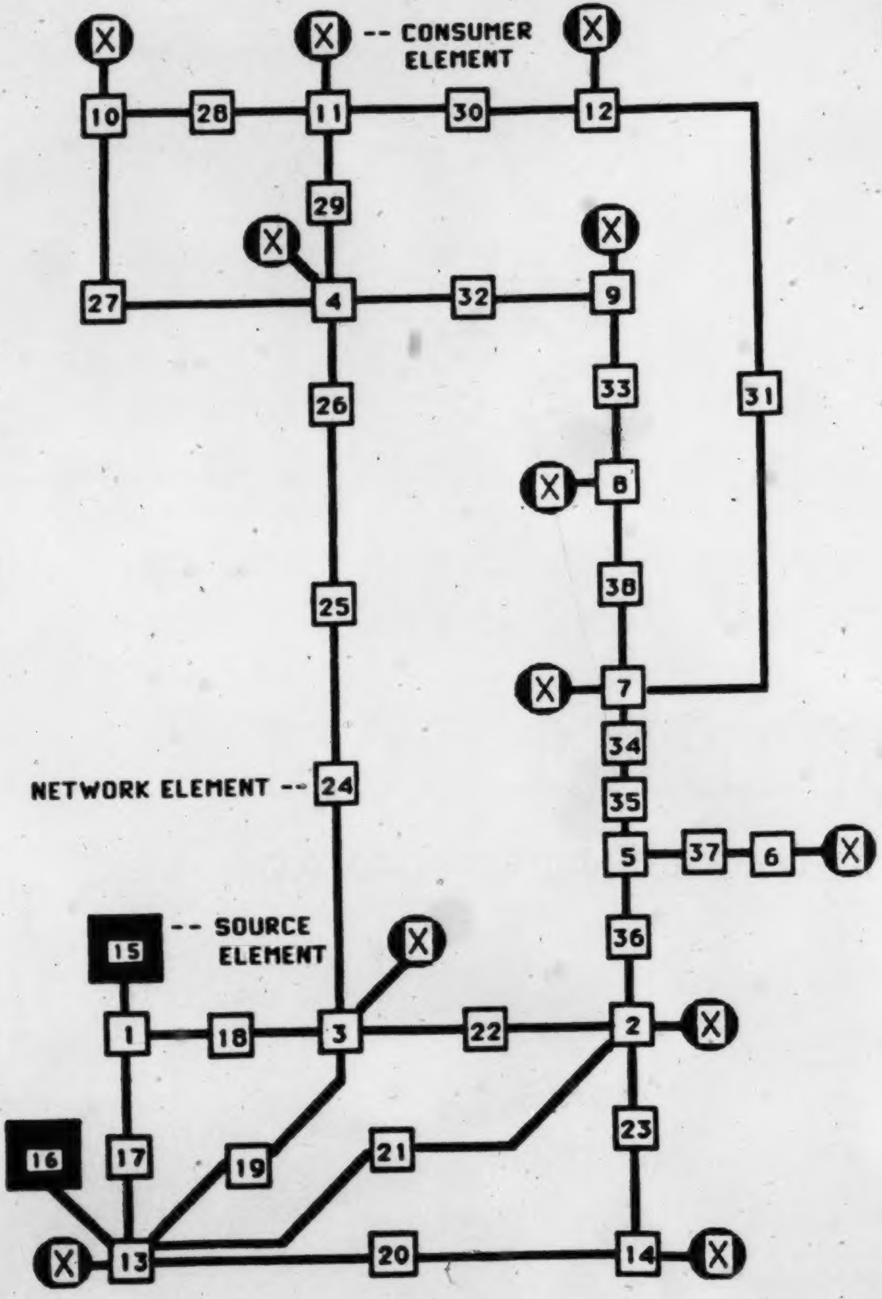

X
-- CONSUMER ELEMENT
10
28
11
30
12
29
4
27
32
9
33
31
26
8
38
25
7
34
NETWORK ELEMENT --
24
35
5
37
6
36
15
-- SOURCE ELEMENT
1
18
3
22
2
16
17
19
21
23
13
20
14

Figure 2.7. Element block diagram of Figure 2.6.

ith Element	jth Adjacent Connecting Elements				
1	15	17	18		
2	22	23	21	36	
3	18	24	22	19	
4	26	27	29	32	
5	35	36			
6	37				
7	34	31	38		
8	33	38			
9	32	33			
10	27	28			
11	28	29	30		
12	30	31			
13	16	17	19	20	21
14	20	23			
15	-1	1			
16	-1	13			
17	1	13			
18	1	3			
19	3	13			
20	13	14			
21	2	13			
22	2	3			
23	2	14			
24	3	25			
25	24	26			
26	4	25			
27	4	10			
28	10	11			
29	4	11			
30	11	12			
31	7	12			
32	4	9			
33	8	9			
34	7	35			
35	5	34			
36	2	5			
37	35				
38	7	8			
999	38				

Figure 2.8 Adjacent connecting elements array ACE(i,j) of the network shown in Figure 2.7.

The adjacent connecting elements (i.e., the jth column of ACE(i,j)) are identified for each element in the network from the element block diagram. For example, load element numbered 3 in Figure 2.7 has four adjacent connecting elements (i.e., elements #18, #19, #22 and #24). If a particular element is a source element (e.g., a generator) then one of its adjacent connecting element is set equal to '-1'. The ACE(i,j) array is the basic input data required to identify the operational paths from the network source nodes to any selected critical node.

The last row of the ACE(i,j) array (i.e., the 999th element) is used to initialize of the tracing process of the operational paths (i.e, the null * element in the previous section). Its adjacent connecting element is set to any arbitrary number, e.g., the total number of components in the network configuration (i.e., the N of section 2.1). For this case study the total number is 38, as shown in Figure 2.8. Note that 999 is an arbitrary number.

2.3.2 Formation of the PATH(k,l) Array

Once the ACE(i,j) array has been defined, then the operational paths of the network can be traced. The basic procedure for determining the operational paths between a single consumer node and set of network source elements is to first select the last element (i.e., element 999) as the critical element and scan the ACE(i,j) array for the adjacent connecting element of this selected critical element. This adjacent connecting element is then changed to the selected consumer element within the network configuration (i.e., the selected consumer element or node becomes the adjacent connecting element of the selected critical element (i.e., element 999). The adjacent connecting elements of this critical element then become the new selected elements ~~and their~~ adjacent connecting elements are found from the ACE(i,j) array. The procedure is repeated until all possible operational paths are found. Many of the paths which form loops or incomplete paths are dropped during the tracing process. The checking and dropping process is done each time to save the computer processing time and storage. Only those paths that begin with a source element and end with the selected consumer load point are considered as valid paths. Figure 2.9 shows the PATH array for consumer load point #3 within the network configuration shown in Figure 2.7. A visual examination of Figures 2.7, 2.8 and 2.9 provides sufficient insight into the computer tracing algorithm described.

Path #		Elements Within Path											
1		15	1	18	3								
2		16	13	19	3								
3		16	13	17	1	18	3						
4		16	13	21	2	22	3						
5		15	1	17	13	19	3						
6		16	13	20	14	23	2	22	3				
7		15	1	17	13	21	2	22	3				
8		15	1	17	13	20	14	23	2	22	3		
9		16	13	21	2	36	5	35	34	7	38	8	33
	...		9	32	4	26	25	24	3				
10		16	13	21	2	36	5	35	34	7	31	12	30
	...		11	29	4	26	25	24	3				
11		16	13	20	14	23	2	36	5	35	34	7	31
	...		12	30	11	29	4	26	25	24	3		
12		16	13	20	14	23	2	36	5	35	34	7	38
	...		8	33	9	32	4	26	25	24	3		
13		16	13	21	2	36	5	35	34	7	31	12	30
	...		11	28	10	27	4	26	25	24	3		
14		15	1	17	13	21	2	36	5	35	34	7	38
	...		8	33	9	32	4	26	25	24	3		
15		15	1	17	13	21	2	36	5	35	34	7	31
	...		12	30	11	29	4	26	25	24	3		
16		16	13	20	14	23	2	36	5	35	34	7	31
	...		12	30	11	28	10	27	4	26	25	24	3
17		15	1	17	13	20	14	23	2	36	5	35	34
	...		7	38	8	33	9	32	4	26	25	24	3
18		15	1	17	13	20	14	23	2	36	5	35	34
	...		7	31	12	30	11	29	4	26	25	24	3
19		15	1	17	13	21	2	36	5	35	34	7	31
	...		12	30	11	28	10	27	4	26	25	24	3
20		15	1	17	13	20	14	23	2	36	5	35	34
	...		7	31	12	30	11	28	10	27	4	26	25
	...		24	3									

Figure 2.9 PATH array for consumer element #3.

The number of operational paths to a particular consumer element is dependent upon its physical location within a given network configuration with respect to the set of network source nodes. The task of manually determining the number of operational paths to an element is an extremely time consuming and error prone process. The use of digital computer algorithm simplified this task considerably. The number of operational paths to each consumer element contained within the network configuration of Figure 2.7 is shown in Table 2.3.

Table 2.3 Number of operational paths for each consumer element.

Consumer Element	Number oF Operational Paths To Consumer Success
2	22
3	20
4	38
6	34
7	34
8	54
9	54
10	64
11	54
12	54
13	11
14	26
OVERALL	465

It can be seen from Table 2.3 that the variation in the number of operational paths to each consumer element is quite significant demonstrating the finding that the location of consumer element within a network configuration has a significant impact on the continuity of flow that the consumer element or node receives.

2.3.3 Removal of Network Elements

When physical elements are removed (e.g., forced out of service) from a given network configuration the number of operational paths to a particular consumer element are significantly affected. For example, if the network source element #15 and element #5 are removed simultaneously from the original network configuration (i.e., the IEEE 14 bus network configuration in Figure 2.6), the number of operational paths for consumer element #3, for example are significantly reduced as shown in Figure 2.10. It can be seen from Figure 2.10 that the number of operational paths is only four while in the original network configuration it was twenty. Table 2.4 shows the drop in the number of paths to each consumer element when two network elements (i.e., 5 and 15) are removed from the network configuration.

Path #	Elements Within Path							
1	16	13	19	3				
2	16	13	17	1	18	3		
3	16	13	21	2	22	3		
4	16	13	20	14	23	2	22	3

Figure 2.10 Network PATH array for consumer element #3 with source element #15 and element #5 removed.

Table 2.4 Number of operational paths for each consumer element with source element #15 and element #5 removed.

Consumer Element	Number oF Operational Paths To Consumer Success
2	4
3	4
4	4
6	12
7	12
8	12
9	12
10	12
11	12
12	12
13	1
14	4
OVERALL	101

The operational paths in Figure 2.9 and Figure 2.10 link all the network source nodes to a single consumer element. However, depending upon the network study involved, the operational paths can be redefined in many ways. For example, the operational paths can be defined as the paths:

- from a single source node to a critical consumer element;
- from a set of source nodes to a critical element;
- from a single or set of source nodes to a set of consumer elements;
- which are within the network element flow capacity limits.

This chapter has presented and applied a computer algorithm and model which can easily trace the operational paths to any consumer load point contained within a given distribution network configuration. These paths provides the basic knowledge of a network required by the reliability methodology presented and discussed in the remaining Chapters in the thesis.

CHAPTER III

RELIABILITY AND FAILURE FREQUENCY

3.1 Cut Set Technique

A 'cut-set' is defined as a set of components whose failure will cause a system to fail and a minimal cut-set contains the lowest number of components whose failure alone will cause system failure. For example, the system in Figure 3.1 has five cut-sets and two minimal cut-sets. The components in the cut-sets and minimal cut-set are shown in Tables 3.1 and Table 3.2. The order of a cut-set is the number of components whose failure will cause the system to fail. Note: a system failure occurs when the elements serving the load are isolated from the source by link failures.

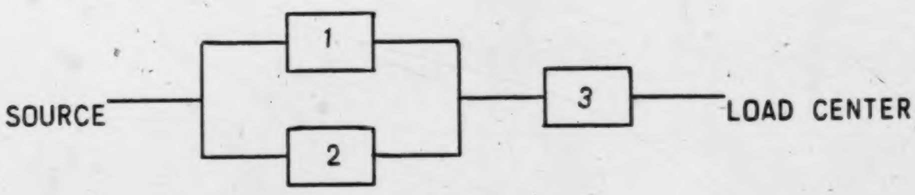


Figure 3.1 Simple system to illustrate the cut-set approach.

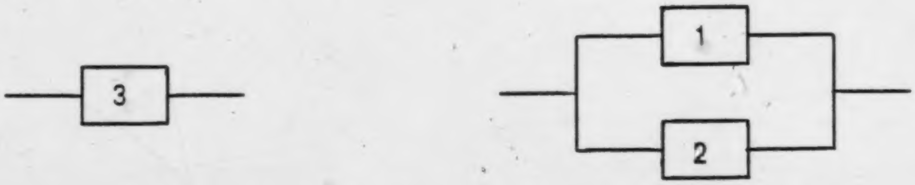
Table 3.1 Components in cut sets.

Cut-set	Components in cut	Cut-set order
1	3	1
2	1 2	2
3	1 3	2
4	2 3	2
5	1 2 3	3

Table 3.2 Components in minimal cut-sets.

Cut-set	Components in minimal cut
1	3
2	1 2

The schematic diagram for the minimum cut-sets [15] is shown in Figure 3.2.



First order cut set Second order cut set

Figure 3.2 Minimal cut-sets for system of Figure 3.1.

The components of a minimal cut set of any order greater than one are placed in parallel on the schematic diagram because all of them must fail to cause system failure. The identified minimal cut-sets are then placed in series because any one minimal cut set can cause system failure. Once the minimal cut-sets of a network have been obtained, the reliability levels of the network configuration can be evaluated.

3.2 Evaluation Of Frequency And Duration Of System Outages

In evaluating the frequency and duration of system outages and consumer interruptions, the following basic assumptions are often made in practice [11]:

(i) System is repairable and composed of N independent components, i.e., failure of one component will not affect the performance of any other components;

(ii) Each component can be represented by a 2-state device, and system success or failure can be expressed in terms of these 2-state devices;

(iii) System is remote from the time of origin so that an equilibrium (steady state) condition of failure and repair has been reached.

(iv) Repaired components are as good as new.

3.2.1 Probability of System Failure

A path is formed when a string of elements are connected together from a source to a particular load point within a system. In a set of minimal paths (i.e., the paths can be considered to be parallel), all of the paths must fail in order to isolate the sources from the consumer nodes. A minimal path is a path which contains a minimum number of components, i.e., no elements occur more than once in a path. The minimal path themselves are, however, in series as failure of a component alone will ensures path failure; i.e., the elements forming an operational path are connected in series within the network configuration. The probability of system failure is given as [12]:

$$
\begin{aligned}
P_f &= \Pr\{\bar{C}_1 \cup \bar{C}_2 \cup \bar{C}_3 \ldots\ldots \cup \bar{C}_m\} && \ldots\ldots (1)\\
&= [\,\Pr(\bar{C}_1) + \Pr(\bar{C}_2) + \ldots + \Pr(\bar{C}_m)\,] && \binom{m}{1} \text{ terms}\\
&\quad -[\,\Pr(\bar{C}_1 \cap \bar{C}_2) + \Pr(\bar{C}_1 \cap \bar{C}_3) + \ldots + \\
&\qquad\qquad \Pr(\bar{C}_i \cap \bar{C}_j) + \ldots] && \binom{m}{2} \text{ terms}\\
&\quad +[\,\Pr(\bar{C}_1 \cap \bar{C}_2 \cap \bar{C}_3) + \ldots + \\
&\qquad\qquad \Pr(\bar{C}_i \cap \bar{C}_j \cap \bar{C}_K) + \ldots\,]\\
&\quad \ldots\ldots\ldots\ldots\\
&\quad + (-1)^{m-1}\, \Pr(\bar{C}_1 \cap \bar{C}_2 \cap \ldots \cap \bar{C}_m) && \binom{m}{m} \text{ terms}
\end{aligned}
$$

where: m is the number of cut set ;

$i<j<K$; $i,j,k = 1,2,3,\ldots$;

C_i denotes the minimum cut set of i ;

$\bar{C}_i$ denotes the failure of components in cut set C_i ;

P_f is the probability of system operational failure;

$\binom{m}{i}$ denotes the combinational formula, $\frac{m!}{(m-i)!\ i!}$;

$\cap$ denotes intersection of events

Equation (1) for the probability of system failure does not imply component independence. The terms of the expansion can be calculated when components failures are independent. In the case of dependent failures, calculating the various terms requires a state-space approach, which forfeits the advantage of various network methods. Equation (1) involves the calculation of 2^{m-1} terms. The "m" in expansion (1) is equivalent to the number of valid paths to a consumer load point in the proposed computer model. The term $\overline{C}_i$, on the other hand, represents the failure of components in cut set C_i of the consumer load point.

The system reliability expansion in equation (1) may also be expressed by:

$$\begin{aligned} R &= \text{probability } \{ \text{ at least one path is successful } \} \\ &= \Pr\{ \bigcup_{i=1}^{n} P_i \} \qquad \text{.....} (2) \end{aligned}$$

where U denotes the union of events and n denotes the total number of minimal operational paths.

By use of the expanion rule for union of n events [15], the following expression for the system reliability (i.e., R) is obtained:

$$\begin{aligned} R = {} & \sum_{i=1}^{n} \Pr\{P_i\} - \sum_{i=1}^{n} \sum_{j>i}^{n} \Pr\{P_i \cap P_j\} \qquad \text{.....} (3) \\ & + \sum_{i=1}^{n} \sum_{j>i}^{n} \sum_{k>j}^{n} \Pr\{P_i \cap P_j \cap P_k\} + \ldots + \\ & + (-1)^{n-1} \Pr\{ \bigcap_{i=1}^{n} P_i \} \end{aligned}$$

where $\cap$ denotes the intersection of events.

The total number of terms Z involved in equation (3) is given by:

$$Z = 2^{n} - 1 \qquad \text{.....} (4)$$

which is the same as expansion (1) above.

An example to illustrate the application of equation (3) is defined as follows: consider the simple system shown in Figure 3.1. It is obvious from Figure 3.1 that there are only two possible paths required for system success, 1-3 and 2-3. Let the probability of each component being operational (i.e., R) be 0.9, then from equation (3) the probability of system operational success is as follow, where m is 2:

$$
\begin{aligned}
R &= \Pr\{\text{ 1-3 up }\} + \Pr\{\text{ 2-3 up }\} - \Pr\{\text{ (1-3)}\cap\text{(2-3) up }\} \\
&= [\, R_1 R_3 + R_2 R_3 \,] - [\, R_1 R_2 R_3 \,] \\
&= (\, 0.9*0.9 + 0.9*0.9 \,) - (\, 0.9*0.9*0.9 \,) \\
&= 0.891
\end{aligned}
$$

Note that the Pr{ 1-3 } is $R_1 R_3$ because 1 and 3 are in series with each other. The Pr{ 1-3 ∩ 2-3 } is simply $R_1 R_2 R_3$ since the elements are independent, i.e.,

$$
\begin{aligned}
\Pr\{\text{ 1-3}\cap\text{2-3 up }\} &= \Pr\{\text{ 2-3 up } \mid \text{ 1-3 up }\} \times \Pr\{\text{ 1-3 up }\} \\
&= R_2 \times R_1 R_3
\end{aligned}
$$

The reliability data used in this thesis are steady state probabilities and frequencies of failure of each element. The reliability of each element in the network configuration is found independently within the computer algorithm, from their respective failure rate (λ, failures per year) and restoration and/or repair rate (r, years per repair). The probability of successful operation of an element is evaluated by the following expression [12]:

$$P_e(t) = P_e = \frac{u}{\lambda + u} \qquad \ldots\ldots (5)$$

where: $u = 1/r$, and r is in years per repair;

λ element failure rate in failures per year;

P_e is the steady state probability of an element operating

Steady state probabilities may be easily changed to time dependent probabilities, and/or include average maintenance time by using the appropriate expressions [13].

3.2.2 Consumer Failure Frequency

Consider a minimal cut-set C_i which contains components l and m. If components l and m fail, the system fails irrespectively of the states of the other components. When components of C_i fail, it is equivalent to the system being in subset S_i of state space S, where [14]:

$S_i = \{ S_j :$ in the state S_j, the components l and m are failed and the other components exist in a particular state $\}$

The state $\overset{v}{s}_i$ in which components l and m of C_i are failed and all other components are good is called the vertex state of S_i. The system can transit from the vertex state either upwards (i.e., fewer failed components) by repairing either component l or m or both, or it can transit downwards (i.e., more failed components) by successive failures of other components. The subset S_i consists of the states generated by the downward transitions from s_i^v.

In practice, the state space subsets representing minimal cut-sets overlap and their frequency of occurrence can be derived by referring to Venn diagram below.

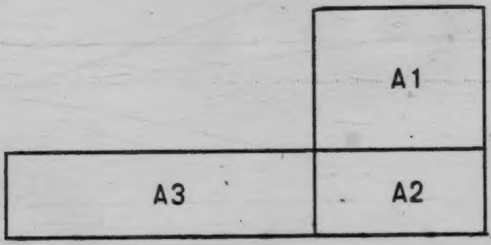


Figure 3.3 Venn diagram for overlapping subsets representing two minimal cut sets, where A1, A2 and A3 are three different minimal cut-sets..

Define:

$$S_i = A_1 \cup A_2 \quad \text{and} \quad S_k = A_3 \cup A_2 .$$

Then

$$F(S_i \cup S_k) = F(S_i) + F(S_k) - F(S_i \cap S_k) \qquad \text{.....} \ (6)$$

$$= \Pr(\bar{C}_i)\bar{u}_i + \Pr(\bar{C}_k)\bar{u}_k - \Pr(\bar{C}_i \cap \bar{C}_k)\bar{u}_{i+k}$$

where C_i and C_k are two different minimal cut-sets with subsets S_i and S_k respectively, and F is the frequency function, and $\bar{u}_i$ is the rate of departure from the fail state(s).

In general, for m cut sets,

$$f_f = F(S_1 \cup S_2 \cup S_3 \; \ldots\ldots \cup S_m) \qquad \ldots\ldots (7)$$

$$= [\, Pr(\bar{C}_1)\bar{u}_1 + Pr(\bar{C}_2)\bar{u}_2 + \ldots + Pr(\bar{C}_m)\bar{u}_m \,] \quad \binom{m}{1} \text{ terms}$$

$$- [\, Pr(\bar{C}_1 \cap \bar{C}_2)\bar{u}_{1+2} + \ldots + Pr(\bar{C}_i \cap \bar{C}_j)\bar{u}_{i+j} + \ldots \,] \quad \binom{m}{2} \text{ terms}$$

$$+ [\, Pr(\bar{C}_1 \cap \bar{C}_2 \cap \bar{C}_3)\bar{u}_{1+2+3} + \ldots + Pr(\bar{C}_i \cap \bar{C}_j \cap \bar{C}_k)\bar{u}_{i+j+k} + \ldots \,]$$

$$\ldots\ldots\ldots\ldots$$

$$+ (-1)^{m-1} \, Pr(\bar{C}_1 \cap \bar{C}_2 \cap \ldots\ldots \cap \bar{C}_m)\bar{u}_{1+2+\ldots+m} \quad \binom{m}{m} \text{ terms}$$

where: f_f is frequency of system failure in the system failure per year ;

$\bar{u}_i$ is sum of u_x where x are the components in C_i ;

$\bar{u}_{i+j+k+\ldots}$ is sum of all u_x over all $x \in (C_i \cup C_j \cup C_k \cup \ldots)$; i.e., the sum of the repair rates of the components which belong to any or all of the cut-sets $C_i, C_j, C_k \ldots$

The total down time per annum and the system failure rate at the consumer node may be found from expression (8) and (9) respectively.

Total annual downtime for a particular consumer node = $(P_f * 8760.)$ hrs/yr ..... (8)

Consumer failure rate $(\lambda s) = f_f \,/\, P_s$ f/yr ..... (9)

where: P_f is the probability of system/network failure, unavailability

P_s is the probability of system/network success, availability

f_f is the frequency of system failure

$P_s + P_f = 1.0$

3.3 Examples

3.3.1 Example 1: Unidirectional Elements

Consider the network shown in Figure 3.4 below. The input data for the system (i.e, the ACE(i,j) array) is shown in Figure 3.5.

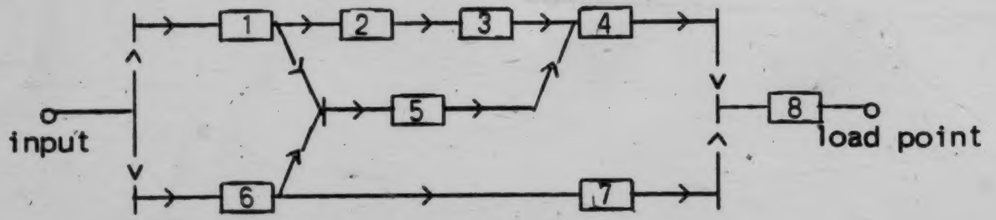


Figure 3.4 Unidirectional elements network configuration.

ith Element	jth Adjacent Connecting Elements	
1	-1	
2	1	
3	2	
4	3	5
5	1	6
6	-1	
7	6	
8	4	7
999	8	

Figure 3.5 ACE(i,j) array for the system in Figure 3.4.

The operational paths and the reliability levels for the system shown in Figure 3.4 is shown in Table 3.3 below.

Table 3.3 The reliability levels and routing patterns of the system configuration in Figure 3.4.

- all elements reliability levels = 0.9
- element #8 reliability level = 1.0

Path #	Elements Within Path				
1	1	2	3	4	8
2	6	7	8		
3	1	5	4	8	
4	6	5	4	8	

System reliability level is: 0.9682659
System downtime is: 277.9902 hrs/yr
System failure frequency is: 2.2950903 f/yr
System failure rate is: 2.37031 f/yr

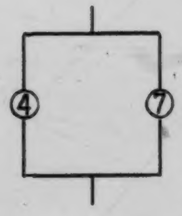
The system reliability in Figure 3.4 was computed manually to show that the results shown in Table 3.3 are similar to those obtained by a classical method. In this case BAYE'S theorem was used according to the following steps.

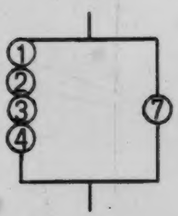
R_s = R(component 6 is good)xR_6 + R(component 6 is bad)xQ_6

where: R_s is the system operational success
R_6 is the probability of success of component 6
Q_6 is the probability of failure of component 6

Given component 6 is good:

R_s(6 is good) = R(5 is good)xR_5 + R(5 is bad)xQ_5

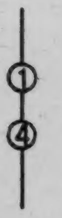


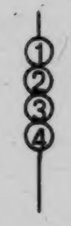


$= (0.9+0.9-0.9^2)\text{x}0.9 + (0.9^4+0.9-0.9^4\text{x}0.9)\text{x}(1.-0.9)$
$= 0.987561$

Given 6 is bad:

R_s(6 is bad) = R(5 is good)xR_5 + R(5 is bad)xQ_5





$= (0.9^2\text{x}0.9+0.9^4\text{x}0.1)$
$= 0.79461$

Therefore, the system reliability is:

$$R_s = 0.9 \times 0.987561 + (1.-0.9) \times 0.79461 = 0.9682659$$

As can be seen the manually obtained reliability level is the same as the value listed in Table 3.3.

3.3.2 Example 2: Bridge Network

Table 3.4 is the summary of the results obtained when the proposed model was applied to the existing published network [14] using the reliability data (i.e., the failure rate and repair rate) given. Note that the nodes of the bridge network, Figure 3.6 are renumbered. Each of the junction nodes was assumed to be 100% reliable. The element block diagram and the ACE(i,j) array of the bridge network in Figure 3.6 are shown in Figure 3.7 and Figure 3.8.

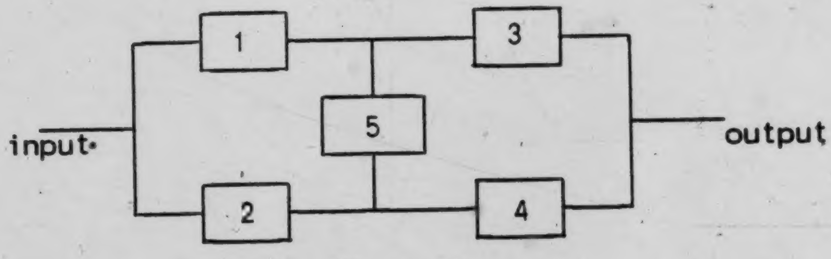


Figure 3.6 Bridge network.

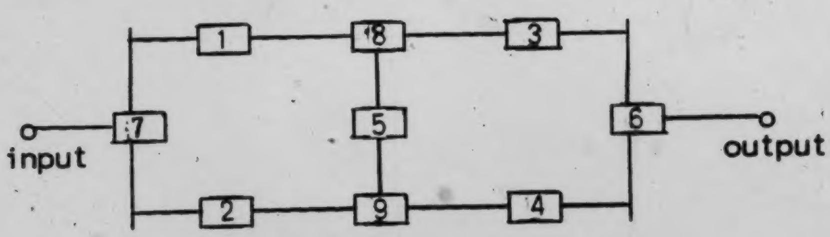


Figure 3.7 Element block diagram of Figure 3.6.

ith Element	jth Adjacent Connecting Elements	
1	7	
2	7	
3	8	
4	9	
5	8	9
6	3	4
7	-1	
8	1	5
9	2	5
999	9	

Figure 3.8 ACE(i,j) array of Figure 3.7.

Table 3.4 Output node reliability indices for the bridge network.

- all components have an assumed repair rate of 20.0 hours

Component	Output Node Reliability Indices			
Failure rate (f/yr)	Availability	Failure frequency (f/yr)	Failure rate (f/yr)	Total annual downtime (hrs/yr)
2.0	0.9999584556	0.0364414	0.03645	0.3636
4.0	0.9998347163	0.1453753	0.14540	1.4476
8.0	0.9993454814	0.5779632	0.57834	5.7336
16.0	0.9974359870	2.2777741	2.28363	22.460
32.0	0.9902020693	8.7691411	8.85591	85.829
219.0	0.7572016120	201.87655	266.609	2126.9

The results shown in Table 3.4 are similar to those obtained in reference [14], where the system failure rate is evaluated using the equation shown in reference [14].

3.4 Reliability Levels Of Case Study

The basic reliability data (i.e., the failure rates and restoration or repair rates of each element) for the distribution network configuration shown in Figure 2.7 (IEEE 14 bus network) is tabulated in Table 3.5. The reliability of the network configuration from the perspective of an individual consumer load point will be examined first. Approximate equations are used to evaluate individual consumer reliability levels. References [11] and [16] show the error involved in evaluating the failure and repair rates using the approximated cut-set equations and the error involved in limiting the order of cut-set to third order.

Table 3.5 Elements failure and repair rates of Figure 2.7

Element #	Failure Rate (f/yr)	Restoration/repair Rate (hrs/repair)
1	0.1250	12.00
2	0.1250	12.00
3	0.1250	12.00
4	0.1250	12.00
5	0.1250	12.00
6	0.1250	12.00
7	0.1250	12.00
8	0.1250	12.00
9	0.1250	12.00
10	0.1250	12.00
11	0.1250	12.00
12	0.1250	12.00
13	0.1250	12.00
14	0.1250	12.00
15	0.3200	165.00
16	0.3200	165.00
17	0.9450	42.50
18	1.1340	42.50
19	0.7560	42.50
20	1.5120	42.50
21	1.5120	42.50
22	0.9450	42.50
23	0.7560	42.50
24	0.1890	42.50
25	0.3000	174.00
26	0.1890	42.50
27	0.9450	42.50
28	0.7560	42.50
29	0.9450	42.50
30	0.7560	42.50
31	0.9450	42.50
32	0.5670	42.50
33	0.3790	42.50
34	0.3790	42.50
35	0.3000	174.00
36	0.3790	42.50
37	0.1890	42.50
38	0.1890	42.50

The reliability analysis of any consumer element is dependent upon many assumptions that must be validated in practice. For example, the failure rate of any path or element may NOT be independent. In these conditions, the coupled relationships between the elements and paths must be established prior to any reliability analysis. For the sake of simplicity, the operational paths of the network shown in Figure 2.7 will be assumed to be independent. The consumer reliability levels were calculated for each consumer element in the network and are shown in Table 3.6. The failure rate and the duration of outages for each consumer load point/center as shown in Table 3.6 were evaluated using the equations contained in reference [15], limited to the third order minimal cut-set. The m-th order of cut is defined as combination of all the the elements in which m number of cuts can form a successful operational path. Note that the results in Table 3.6 do not take into consideration any weather factors. However, consumer reliability indices change when the effect of weather are considered. This factors will be considered in the Chapter V and VI.

Table 3.6 Consumer reliability indicies of the case study - weather factors are not included

Load point	Availability	Consumer failure frequency (f/yr)	Consumer failure rate (f/yr)	Average duration of interruption (hrs/r)	Total annual downtime (hrs/yr)
2	0.9997892	0.131520	0.131548	14.0383	1.8467
3	0.9997892	0.131446	0.131474	14.0424	1.8462
4	0.9997077	0.151372	0.151417	16.9155	2.5613
6	0.9929408	0.625856	0.630305	98.8070	62.2786
7	0.9997073	0.151778	0.151822	16.8954	2.5651
8	0.9997006	0.155737	0.155784	16.8429	2.6238
9	0.9996969	0.157400	0.157447	16.8684	2.6559
10	0.9996864	0.162350	0.162401	16.9190	2.7477
11	0.9997046	0.154128	0.154174	16.7907	2.5887
12	0.9996939	0.158823	0.158872	16.8809	2.6819
13	0.9997913	0.129714	0.129741	14.0947	1.8287
14	0.9997604	0.144406	0.144440	14.5328	2.0991
OVERALL	0.9910146	2.013712	2.031970	39.0878	79.4253

In the evaluation of consumer element reliability levels, it is important to note that the set of paths from the source nodes to an individual consumer element are usually unique. The failure frequency of the system is dependent on the reliability levels of the consumer elements and also the location of the consumer element as can be seen from Table 2.2 and Table 3.6 above; i.e., the more operational paths to a consumer load point the lesser the chances of the consumer having no service. Table 3.7 illustrates a change in load point reliability levels when the network configuration is altered. For example, source element #15 and element #5 are removed from the network configuration to illustrate the change in reliability levels.

Table 3.7 Consumer reliability levels with source element #15 and element #5 removed.

Load point	Availability	Consumer failure frequency (f/yr)	Consumer failure rate (f/yr)	Average duration of interruption (hrs/r)	Total annual downtime (hrs/yr)
2	0.9936701	0.566642	0.570252	97.8575	55.8034
3	0.9936703	0.566507	0.570116	97.8776	55.8016
4	0.9858685	1.353711	1.373116	91.4465	125.5666
6	0.9771055	2.452368	2.509829	81.7805	205.2550
7	0.9856634	1.495083	1.516829	84.0009	127.4150
8	0.9856656	1.493899	1.515625	84.0548	127.3955
9	0.9856756	1.488715	1.510350	84.2885	127.3051
10	0.9856847	1.484396	1.505954	84.4800	127.2231
11	0.9857016	1.477011	1.498436	84.80232	127.0708
12	0.9856742	1.490031	1.511687	84.2224	127.3178
13	0.9998288	0.444924	0.445000	122.022	54.3000
14	0.9936424	0.578728	0.582430	96.2329	56.0489
OVERALL	0.9759243	3.317372	3.399210	63.5755	216.1063

The order of ties (i.e., union) in the study is limited to 13, where a k-th order tie is defined as the number of minimal paths to be unioned in expression (3). For example, Pr{ A1 U A2 U A3 } is a third order tie, and a k-th order tie is Pr{ A1 U A2 U ..... U Ak }. Note that the maximum number of ties is equal to the maximum number of paths. The error involved in stopping the order of tie between 13 and 14 is very small, approximately 0.00001%. Therefore, the results shown in this Chapter are acceptable for the given data of the network configuration.

The flow graph technique allows an easy and fast method of determining all the paths for system operational success and each consumer's reliability characteristics. For example, to evaluate the overall system/consumer reliability indices and the operational paths of a consumer load element with 10 operational paths (i.e., a 10 order of tie set) the proposed algorithm and model takes about 0.697 seconds on AMDAHL 580/5860 at the University of Alberta. If these calculations were to be done manually, it could take several hours or longer to complete.

In the proposed algorithm, the component reliability levels were based on the duration of repair or replacement and circuit transfer activities. However, in many industrial systems, the duration of the outage may cause many industrial processes to be down for a duration far exceeding the restoration activities. In these cases the restarts times of the processes would be used in the reliability calculations.

CHAPTER IV

RELIABILITY EVALUTION OF A DISTRIBUTION NETWORK CONFIGURATION

4.1 The Distribution Network

The proposed path algorithm was applied to an actual complex distribution system, i.e., The University of Alberta power distribution network as shown in Appendix B. Two of its load centers, i.e., General Service Building and Civil -Electrical Engineering Building, were examined in detail (e.g., reliability levels). The block diagram (i.e., the numbering of the elements) of the distribution network configuration of The University of Alberta electrical power distribution network is shown in Appendix B, Figure B.1.

4.2 Data Input

The distribution network steady state reliability indices (i.e., frequency and duration of interruptions) were evaluated from the failure rates and restoration rates of the components within the network configuration. Table 4.1 shows the failure and restoration/repair rates for the respective elements of Figure B.1. The adjacent connecting element (ACE(i,j)) array of the network configuration is shown in Figure C.1 of Appendix C. Table 4.2 summaries the operating conditions of the switches (i.e., whether they are normally opened or closed) in the network for two periods, February 1983 and September 1985.

Table 4.1 Element's failure and restoration/repair rates of Figure B.1.

Components	Failure Rate(f/yr)	Restoration Rate(hrs/f)
Transformers:		
- liquid (all size)	0.0041	529.0
- dry (0 - 15kV)	0.0036	153.0
- oil	0.0037	61.0
Circuit Breakers:		
- below 600V	0.0044	4.7
- above 600V	0.0176	10.6
Motors:		
- induction (601 - 15kV)	0.0404	76.0
- synchronous (601 - 15kV)	0.0318	175.0
Generators:		
- gas turbine	0.6380	23.1
Switches:		
- enclosed	0.0061	3.6
Bus Ducts:		
- all voltages	0.000125	128.0
Cables:		
- all types of insulation, in duct or conduit below ground	0.00613 (per 1000 feets)	96.8
Cable Joints:		
- in duct or conduit below ground, (601 - 15kV)	0.000864	36.1

The data shown in Table 4.1 was obtained from " IEEE Recommended Practice for Design of Reliable Industrial and Commercial Power Systems " (Gold Book) [11]. The length of cables of the University system was approximated from a previous study of the system [17].

Table 4.2 The switches that are open in the network in Feb. '83 and Sept. '85.

(i) February 1983 (Figure B.1 configuration)

161	162	165	166	223	281	305	381	398	407
408	409	410	464	465	466	467	468	618	619
620	621	622	623	624	625	658	659	660	661
910	911	912	913	916	918	921	923	927	930
933	936	939	942	955	967	970	1199		

(ii) September 1985

73	74	161	162	165	166	281	305	381	398
407	408	409	410	443	446	448	449	464	468
618	619	620	621	622	623	624	625	658	659
660	661	824	825	910	912	913	916	918	921
923	927	930	933	936	939	942	955	967	970
1199									

4.3 Results

The reliability indices, i.e., the consumer failure frequency, interruption duration and the routing patterns of the two selected consumer load points in the configuration shown in Figure B.1 (i.e., the network in February 1983) are tabulated in Tables 4.3 and 4.4. The operational paths to these selected consumer loads for September 1985 configuration are also shown in the table.

Table 4.3 Reliability indices of the two selected consumer load points of the University of Alberta distribution network.

Consumer load point	Availability	Failure frequency (f/yr)	Failure rate (f/yr)	Repair rate (hrs/f)	Annual downtime (hrs/yr)
General Service Bldg.	0.9999999	1.0000457	1.0000458	0.000855	0.000876
Civil-Elect. Engg.	0.9996435	1.0850518	1.0854387	2.877864	3.122940

Table 4.4 The operational paths to the two selected consumer load points, at 1983 and 1985.

(a) General Service Building :

(i) September 1985 configuration

Path #		Elements within path								
1		34	25	59	314	312	310	308	223	221
	...	214	212	210	208	217	225	229	239	249
	...	258	275	301	302					
2		32	22	58	319	321	323	309	220	222
	...	215	213	211	209	216	224	228	238	248
	...	257	276	303	304					
3		32	24	34	25	59	314	312	310	308
	...	223	221	214	212	210	208	217	225	229
	...	239	249	258	275	301	302			
4		15	19	32	22	58	319	321	323	309
	...	220	222	215	213	211	209	216	224	228
	...	238	248	257	276	303	304			
5		34	24	32	22	58	319	321	323	309
	...	220	222	215	213	211	209	216	224	228
	...	238	248	257	276	303	304			
6		15	19	32	24	34	25	59	314	312
	...	310	308	223	221	214	212	210	208	217
	...	225	229	239	249	258	275	301	302	

(ii) February 1983 configuration

Path #		Elements within path								
1		1	4	50	61	69	177	73	76	78
	...	204	206	208	217	225	229	239	249	258
	...	275	301	302						
2		13	7	51	62	64	75	72	74	77
	...	79	205	207	209	216	224	228	238	248
	...	257	276	303	304					
3		32	22	58	319	321	323	309	220	222
	...	215	213	211	209	216	224	228	238	248
	...	257	276	303	304					
4		1	4	50	61	65	62	64	75	72
	...	74	77	79	205	207	209	216	224	228
	...	238	248	257	276	303	304			
5		13	6	1	4	50	61	63	69	177
	...	73	76	78	204	206	208	217	225	229
	...	239	249	258	275	301	302			
6		1	6	13	7	51	62	64	75	72
	...	74	77	79	205	207	209	216	224	228
	...	238	248	257	276	303	304			
7		15	19	32	22	58	319	321	323	309
	...	220	222	215	213	211	209	216	224	228
	...	238	248	257	276	303	304			
8		34	24	32	22	58	319	321	323	309
	...	220	222	215	213	211	209	216	224	228
	...	238	248	257	276	303	304			
9		13	6	1	4	50	61	65	62	64
	...	75	72	74	77	79	205	207	209	216
	...	224	228	238	248	257	276	303	304	
10		44	45	46	47	48	49	3	1	4
	...	50	61	63	69	177	73	76	78	204
	...	206	208	217	225	239	249	258	275	301
	...	302								
11		44	45	46	47	48	49	3	1	4
	...	50	61	65	62	64	75	72	74	77
	...	79	205	207	209	216	224	228	238	248
	...	257	276	303	304					
12		44	45	46	47	48	49	3	1	6
	...	13	7	51	62	64	75	72	74	77
	...	79	205	207	209	219	224	228	238	248
	...	257	276	303	304					

(b) Civil-Electrical Engineering Building :

Both 1983 and 1985 network configurations have the same impact on the load center, i.e., the new operating conditions of the switches does not affect the routing patterns to the selected load center.

Path #	Elements within path
1	32 21 317 441 455 269 500 539 587 ... 645 691 730 770 787
2	15 19 32 21 317 441 455 269 500 ... 539 587 645 691 730 770 787
3	34 24 32 21 317 441 455 269 500 ... 539 587 645 691 730 770 787

The General Service Building has a higher number of operational paths feeding it than the Civil-Electrical Engineering Building, resulting in a significantly higher level of reliability. Other load centers within the University of Alberta's distribution network were not studied due to a lack of computer funds. However, the two selected load centers are representative of load centers that are within the network configuration.

CHAPTER V

MAINTAINABILITY

5.1 Preventive Maintenance

One of the important operating cost decisions that must be made by the management of any utility plant is how much money should be spent for scheduled electrical preventive maintenance. The amount of maintenance performed on electrical equipment can significantly affect the failure rate of the equipment installed in any system. The maintenance effort varies proportionally with the maintenance cost [12]. Lack of any maintenance will increase the failure rate of the electrical components in a power system and can significantly increase the costs for corrective maintenance activities when the components fail.

Electrical preventive maintenance usually receives meager emphasis in the design phase of an electric distribution system when in fact it can be a key factor to high reliability. Large expenditures for electric systems are made to provide the desired reliability; however, failure to provide timely and high quality preventive maintenance leads to system or component malfunctions or failures, which is a costly proposition.

The distribution system configuration should be designed so that maintenance work is permitted without load interruption or with a minimal outage duration. Often, equipment preventive maintenance and load interruptions may be deferred for critical loads or to portions of the distribution system because of the impact of scheduled outages. To overcome this problem it may be required to install alternate electrical equipment and circuits to permit routine or emergency maintenance on one circuit while the active circuit supplies the critical load during the maintenance period.

In Chapter III, the system failure rate was assumed to be constant as shown in Figure 5.1.

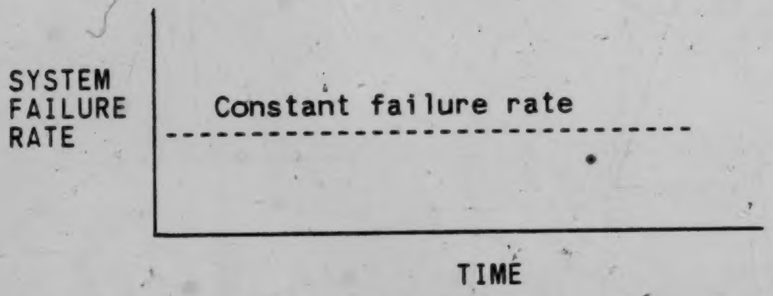


Figure 5.1 The system performance model of Chapter III.

This will not be the case if components are removed from service for periodic inspections and maintenance (i.e., not immediate replacement) in accordance with a planned program. During such a period the capacity available for for service is not constant and therefore the reliability indices for the consumers will be different from those shown in Chapter III where only passive (time independent) failures were considered.

The reliability indices (i.e., with the consideration of maintenance periods of the components) for the consumers within the IEEE 14 bus network configuration (i.e., see Figure 2.7) are evaluated to illustrate the significant effects of maintainability on the system reliability levels. The weather conditions (normal or adverse) also have a significant impact on the maintainability performance of the system. The two possible cases during maintenance periods are considered which are:

(i) weather cannot change during maintenance period;
(ii) weather can change during maintenance period.

The case where weather can change during maintenance periods is subdivided into two further possibilities:

(i) repair is carried on in adverse weather; and
(ii) repair is discontinued in adverse weather.

Similar techniques (e.g., minimum cut set method) are used in the evaluation of consumer reliability indices (outage rate and outage duration). The minimum cut set equations for the outage durations and outage rates for the study are presented in the Appendix D.

5.2 Case Study

The data used for the study of the IEEE 14 bus network configuration is shown in Table 5.1. Note that the permanent failure rate and restoration rate of the components are similar to those listed in Chapter III, section 3.4. The remaining reliability data was extracted from various publications [15,18,19]. Due to lack of published data, the adverse weather outage duration of the components was set to be equal to the normal weather outage duration.

Table 5.1 Component data for the case study.

Element number	Normal weather outage rate (f/yr)	Normal weather outage duration (hrs)	Adverse weather outage rate (f/yr)	Adverse weather outage duration (hrs)	Maintenance outage rate (o/yr)	Maintenance outage duration (hrs)
1	0.125	12.00	0.625	12.00	0.25	4.00
2	0.125	12.00	0.625	12.00	0.25	4.00
3	0.125	12.00	0.625	12.00	0.25	4.00
4	0.125	12.00	0.625	12.00	0.25	4.00
5	0.125	12.00	0.625	12.00	0.25	4.00
6	0.125	12.00	0.625	12.00	0.25	4.00
7	0.125	12.00	0.625	12.00	0.25	4.00
8	0.125	12.00	0.625	12.00	0.25	4.00
9	0.125	12.00	0.625	12.00	0.25	4.00
10	0.125	12.00	0.625	12.00	0.25	4.00
11	0.125	12.00	0.625	12.00	0.25	4.00
12	0.125	12.00	0.625	12.00	0.25	4.00
13	0.125	12.00	0.625	12.00	0.25	4.00
14	0.125	12.00	0.625	12.00	0.25	4.00
15	0.320	165.00	0.320	165.00	2.00	24.00
16	0.320	165.00	0.320	165.00	2.00	24.00
17	0.945	42.50	4.725	42.50	0.50	36.00
18	1.134	42.50	5.680	42.50	0.50	36.00
19	0.756	42.50	3.780	42.50	0.50	36.00
20	1.512	42.50	7.560	42.50	0.50	36.00
21	1.512	42.50	7.560	42.50	0.50	36.00
22	0.945	42.50	4.725	42.50	0.50	36.00
23	0.756	42.50	3.780	42.50	0.50	36.00
24	0.189	42.50	0.945	42.50	0.50	36.00
25	0.300	174.00	1.500	174.00	1.00	24.00
26	0.189	42.50	0.945	42.50	0.50	36.00
27	0.945	42.50	4.725	42.50	0.50	36.00
28	0.756	42.50	3.780	42.50	0.50	36.00
29	0.945	42.50	4.725	42.50	0.50	36.00
30	0.567	42.50	2.835	42.50	0.50	36.00
31	0.756	42.50	3.780	42.50	0.50	36.00
32	0.567	42.50	2.835	42.50	0.50	36.00
33	0.379	42.50	1.895	42.50	0.50	36.00
34	0.379	42.50	1.895	42.50	0.50	36.00
35	0.300	174.00	1.500	174.00	1.00	24.00
36	0.379	42.50	1.895	42.50	0.50	36.00
37	0.189	42.50	0.945	42.50	0.50	36.00
38	0.189	42.50	0.945	42.50	0.50	36.00

average normal weather duration, N = 200.0 hours
average adverse weather duration, S = 5.0 hours

Note that the ACE(i,j) array of the network configuration is not affected by the maintenance factors of the system, i.e., it is the same as presented in Chapter II.

The reliability indices for each of the consumers being serviced by the IEEE 14 bus power system (Figure 2.7) for all the three cases described in the previous section are tabulated in Tables 5.2 to 5.4.

Table 5.2 Reliability indices when weather cannot change during maintenance period.

Load point	Availability	Consumer failure frequency (f/yr)	Consumer failure rate (f/yr)	Average duration of interruption (hrs/r)	Total annual downtime (hrs/yr)
2	0.9996663	0.386851	0.386980	7.55587	2.9240
3	0.9996664	0.386737	0.386866	7.55626	2.9233
4	0.9995530	0.422593	0.422782	9.26527	3.9172
6	0.9881485	2.366601	2.394965	43.8684	105.064
7	0.9995524	0.423128	0.423318	9.26583	3.9224
8	0.9995378	0.431975	0.432175	9.37299	4.0508
9	0.9995325	0.434437	0.434640	9.42753	4.0976
10	0.9995219	0.439589	0.439799	9.52812	4.1908
11	0.9995482	0.427182	0.427376	9.26452	3.9594
12	0.9995313	0.434915	0.435119	0.94396	4.1073
13	0.9996694	0.383871	0.383997	7.54515	2.8973
14	0.9996266	0.405181	0.405332	8.07205	3.2719
OVERALL	0.9849937	6.464809	6.563299	20.3339	133.458

Table 5.3 Reliability indices when weather can change during maintenance period - repair is carried on in adverse weather.

Load point	Availability	Consumer failure frequency (f/yr)	Consumer failure rate (f/yr)	Average duration of interruption (hrs/r)	Total annual downtime (hrs/yr)
2	0.9993572	0.563214	0.563577	9.99779	5.6345
3	0.9993989	0.521606	0.521919	10.0953	5.2690
4	0.9985213	0.914769	0.916123	14.1604	12.973
6	0.9876728	2.678558	2.711989	40.3150	109.334
7	0.9983901	0.994881	0.996485	14.1751	14.125
8	0.9984190	0.965563	0.967092	14.3434	13.872
9	0.9984568	0.941074	0.942528	14.3644	13.539
10	0.9982638	1.055566	1.057402	14.4081	15.235
11	0.9981230	1.132149	1.134278	14.5230	16.473
12	0.9982260	1.075197	1.077108	14.4535	15.568
13	0.9993990	0.522306	0.522620	10.0793	5.2676
14	0.9993148	0.576523	0.576919	10.4120	6.0069
OVERALL	0.9834342	7.357569	7.481507	19.7234	147.561

Table 5.4 Reliability indices when weather can change during maintenance period - repair is discontinued in adverse weather.

Load point	Availability	Consumer failure frequency (f/yr)	Consumer failure rate (f/yr)	Average duration of interruption (hrs/r)	Total annual downtime (hrs/yr)
2	0.9983278	0.430161	0.430881	34.0524	14.673
3	0.9983400	0.410363	0.411045	35.4371	14.566
4	0.9975996	0.517208	0.518453	40.6564	21.078
6	0.9694398	2.441644	2.518613	109.642	276.146
7	0.9975374	0.616483	0.618005	34.9924	21.626
8	0.9974550	0.613160	0.614725	36.3595	22.351
9	0.9974337	0.577021	0.578506	38.9606	22.539
10	0.9973191	0.576199	0.577748	40.7578	23.548
11	0.9975172	0.591560	0.593032	36.7660	21.803
12	0.9973838	0.612467	0.614073	37.4185	22.978
13	0.9983611	0.405521	0.406187	35.4031	14.380
14	0.9979934	0.449635	0.450539	39.0940	17.613
OVERALL	0.9529444	6.584799	6.909951	62.5998	432.562

As can be seen from the tables above, each network constraint affects the system reliability levels differently. These results are obviously different from those in Chapter III, where the network configuration is assumed to be constant. Comparing the values in Table 5.3 and Table 5.4, it is clear that the consumer failure rates are higher for the case where repair is carried on in adverse weather during maintenance period than the case where repair is discontinued in adverse weather. When repair activities are carried on in adverse weather the components within the given configuration are exposed to the extreme elements of the weather which in turns increases the failure rate of the electrical components.

The impact of the decision to perform repair activities or not to during adverse weather conditions has a significant impact on the duration of interruptions. The duration of outages is higher when the repair activities are curtailed during adverse weather periods.

CHAPTER VI

TRANSIENTS

6.1 Transient Faults

Faults can be classified as permanent or transient. Permanent faults are often caused by catastrophic failures of the components. The failure of the component in these cases are irreversible and permanent and requires repair or replacement activities to restore the component to a functioning state. These faults are often characterized by a long outage duration and have a failure rate proportional to the environmental conditions.

Transient faults, on the other hand, are caused by temporary malfunctions of components or usually by external interference such as electrical noise, switching transients and power dips, surges, motor starting, etc. . These faults are of limited duration and although they require restoration, no repair or replacement activities are usually involved. In power systems, the term "transient" generally refers to change in voltage level within less than half a cycle [23]. It is often used to describe any disturbance or interruption that is transitory, such as common mode noise, surges, sags, and other phenomena. Transients are often caused by lightning, capacitor switching, fault switching, arcing ground, and switching inductive loads, such as motors, transformer, or lightning ballasts. Almost all transients, except lightning are generated as the result of the interaction between stored electrical energy in the circuit inductances and capacitances.

6.2 Effects Of Transient Interruption On Consumers

The transient fault on electrical utilities, although of limited duration, can significantly affect both the utilities and its consumers. The impact on an individual consumer depends on the type of consumer he/she is (e.g., industrial, commercial, or residential), and what function the electricity performs for him/her (e.g., lightning, motor drive, or computers).

An interruption of an industrial consumer could result in lost production, damaged equipment, or health hazards. Commercial consumers could suffer a loss in sales, damage to stock, or health hazards to both customers and employees. Interruptions to residential consumers are normally thought to have negligible impact, but a long term interruption can cause monetary losses such as food spoilage due to adverse temperatures; while a short term interruption can cause inconveniences such as housekeeping capacities and food preparation. Interruption to public service locations such as health institutions or hospitals could result in death because emergency units may not be able to perform their intended functions of supplying energy to critial patients (e.g., open heart surgery, etc.) during an interruption.

6.3 Case Study

The effects of temporary outages (transients) on the IEEE 14 bus power system shown in Figure 2.7 will be discussed in this chapter. The data used for the study is shown in Table 5.1. The temporary outage rates of the components for both normal and adverse weather were arbitrarily taken as ten times the values shown in Table 5.1. The effects of component temporary outages overlapping permanent outages and the effects of component temporary outages overlapping maintenance periods on the consumer reliability levels will be studied in detail.

The maintenance periods may be subdivided into two cases, weather cannot change and weather can change (repair carried on or discontinued in adverse weather) during maintenance periods. The minimum cut set equations for the failure rates and outage durations are listed in the Appendix D. The reliability indices of the consumers within network of Figure 2.7 for the above four cases is shown in Tables 6.1 to 6.4.

Table 6.1 Consumer-reliability indices for the case when component temporary outages overlap forced outages

Load point	Availability	Consumer failure frequency (f/yr)	Consumer failure rate (f/yr)	Average duration of interruption (hrs/r)	Total annual downtime (hrs/yr)
2	0.9997892	1.446722	1.447027	1.27621	1.8467
3	0.9997893	1.445904	1.446209	1.27658	1.8462
4	0.9997077	1.665095	1.665582	1.53777	2.5613
6	0.9929408	6.884413	6.933358	8.98255	62.2786
7	0.9997073	1.669558	1.670005	1.53598	2.5651
8	0.9997006	1.713111	1.713624	1.53117	2.6238
9	0.9996969	1.731398	1.731923	1.53349	2.6559
10	0.9996864	1.785846	1.786406	1.53809	2.7477
11	0.9997046	1.695411	1.695912	1.52643	2.5887
12	0.9996939	1.747058	1.747593	1.53462	2.6819
13	0.9997913	1.426855	1.427153	1.28134	1.8287
14	0.9997604	1.588463	1.588844	1.32117	2.0991
OVERALL	0.9910146	22.15084	22.35167	3.55344	79.4253

Table 6.2 Consumer reliability indices for the case when component temporary outages overlap maintenance periods - weather cannot change during maintenance.

Load point	Availability	Consumer failure frequency (f/yr)	Consumer failure rate (f/yr)	Average duration of interruption (hrs/r)	Total annual downtime (hrs/yr)
2	0.9996663	1.701891	1.702460	1.71750	2.9240
3	0.9996664	1.701034	1.701601	1.71795	2.9233
4	0.9995530	1.936082	1.936947	2.02235	3.9172
6	0.9881485	8.594953	8.698037	12.0791	105.064
7	0.9995524	1.940673	1.941542	2.02025	3.9224
8	0.9995378	1.989095	1.990015	2.03555	4.0508
9	0.9995325	2.008176	2.009115	2.03950	4.0976
10	0.9995219	2.062818	2.063805	2.03045	4.1905
11	0.9995482	1.968224	1.969113	2.01077	3.9594
12	0.9995314	2.022891	2.023840	2.02948	4.1073
13	0.9996694	1.680853	1.681409	1.72315	2.8973
14	0.9996266	1.849045	1.849736	1.76883	3.2719
OVERALL	0.9849937	26.47959	26.88300	4.96438	133.458

Table 6.3 Consumer reliability indices for the case when component temporary outages overlap maintenance periods - weather can change during maintenance, repair and maintenace activties continued in adverse weather.

Load point	Availability	Consumer failure frequency (f/yr)	Consumer failure rate (f/yr)	Average duration of interruption (hrs/r)	Total annual downtime (hrs/yr)
2	0.9993572	4.201929	4.204632	1.34007	5.6345
3	0.9993989	3.567922	3.570068	1.47587	5.2690
4	0.9985213	8.610531	8.623282	1.50437	12.973
6	0.9876728	12.79010	12.94973	8.44294	109.334
7	0.9983901	9.743085	9.758795	1.44744	14.125
8	0.9984190	9.363097	9.377924	1.47920	13.872
9	0.9984568	8.995393	9.009296	1.50277	13.539
10	0.9982638	10.57900	10.59740	1.43763	15.235
11	0.9981230	11.83472	11.85697	1.38932	16.473
12	0.998[illegible]260	10.92665	10.94606	1.42224	15.568
13	0.9993990	3.576235	3.578386	1.47207	5.2676
14	0.9993148	4.284402	4.287340	1.40107	6.0069
OVERALL	0.9834342	38.25553	38.89994	3.79336	147.561

Table 6.4 Consumer reliability indices for the case when component temporary outages overlap maintenance periods - weather can change during maintenance, repair and maintenance activities discontinued in adverse weather.

Load point	Availability	Consumer failure frequency (f/yr)	Consumer failure rate (f/yr)	Average duration of interruption (hrs/r)	Total annual downtime (hrs/yr)
2	0.9983279	1.872048	1.875184	7.82458	14.6725
3	0.9983400	1.851105	1.854183	7.85588	14.5662
4	0.9975998	2.208235	2.213548	9.52247	21.0784
6	0.9694398	9.166399	9.455356	29.2053	276.1460
7	0.9975374	2.313057	2.318767	9.32630	21.6255
8	0.9974550	2.360982	2.367006	9.44277	22.3511
9	0.9974337	2.346261	2.352298	9.58153	22.5386
10	0.9973191	2.409791	2.416269	9.74550	23.5478
11	0.9975172	2.319222	2.324995	9.37784	21.8034
12	0.9973838	2.400460	2.406756	9.54777	22.9777
13	0.9983611	1.824822	1.827818	7.86746	14.3803
14	0.9979934	2.057933	2.062071	8.54161	17.6134
OVERALL	0.9529444	27.90290	29.28072	14.7729	432.5615

Comparing the reliability levels of the consumers in the above tables with those in Chapter III (Table 3.6) and Chapter V (Table 5.2 - 5.4), it is clear that when a transient outage occur in a system, the reliability indices of the system (or consumers) changes significantly. Notice that restoration rates during transient are very small as compared to those in Table 3.6 and Table 5.2 to Table 5.4; frequencies of failure, on the other hand, are very much higher. From Table 6.1 to 6.4, it is clear that the consumer reliability level is higher when the preventive maintenance of the components are being considered in the evaluation of the load point reliability levels, however, if repair is carried on during adverse weather conditions during the maintenance periods the reliability level of the load point will be lower as shown in Table 5.3 and Table 5.4.

CHAPTER VII

DISCUSSION AND CONCLUSIONS

7.1 Path Tracing Algorithm

The computer algorithm presented in Chapter II can readily trace and identify the operational paths contained within a given network configuration. Particular consumer elements were selected from the standard IEEE 14 bus power system and the operational paths from various source elements to selected elements were presented. The algorithm was selected on the basis that the junction nodes of the network are considered as elements in the model. Often, the impact of the junction node failures which can significantly alter the routing paths from source nodes of the network to the various load points are not considered in the literature. It was found that the operational paths to various consumer elements are quite unique, and very sensitive to any modification (e.g., removal of network elements) in the network configuration.

7.2 Reliability and Frequency

The steady state reliability and frequency levels of the network viewed from the perspective of the consumer load points were evaluated from the failure rates and repair/restoration rates of each network element. The reliability of each consumer load point was significantly different to demonstrate the point that a consumer location within a given network configuration significantly affects the reliability levels he/she receives.

When components are removed from service, they can have a significant impact on consumer levels of reliability. Chapter III presented an example of removing two elements from the network configuration which demonstrate the changes in the reliability levels and other system indices as seen by various consumers.

In order to evaluate the overall network reliability level and other network performance indices from the perspective of maintaining continuity of service to all consumer elements, it is necessary to follow these procedures:

(i) create a 100% reliable element (i.e., system consumer element);

(ii) link ALL consumer elements in the network to the system consumer element;

(iii) use the computer algorithm to identify the paths and evaluate the network reliability indices as previously discussed in Chapter II and III.

The effect of preventive maintenance of the components has on the consumer levels of reliability is presented in Chapter VI. In Chapter III, only the passive failure of the components was examined.

7.3 Complex Distribution Network

The computer algorithm was applied to The University of Alberta's power distribution network to demonstrate the efficiency of the computer algorithm. The reliability indices of two consumer load points were evaluated and studied in some detail for the complex distribution network, which contains 1300 elements. It is obvious that manually tracing and identifying the operational paths of the network and the evaluation of the consumer reliability levels can be very time consuming and an error prone process. Clearly from the results obtained in Chapter V, it can be concluded that the higher the number of operational paths serving a given location the higher will be the reliability levels for that particular location.

The computer algorithm presented is extremely fast and efficient. No bus or node numbers are required as input data, only the adjacent connecting elements of each element in the network is necessary. Any modifications to the network (e.g., additions or removals) do not have to be recoded, i.e., the original data remains the same and the modifications are handled within the program. The proposed general computer algorithm may be used to solve any type of network configuration, such as communication networks or traffic flow, etc..

7.4 Maintainability

In Chapter V, it can be seen that in the case where component forced outages overlap maintenance periods (with the consideration of normal or adverse weather during the maintenance periods), the consumer interruption frequency was higher when repairs and maintenance activities were continued in adverse weather than those when the activites are discontinued in adverse weather. The consumer interruption durations, on the other hand, were lower when repairs were carried on in adverse weather. The reason for higher frequency of outages and lower interruption durations when repairs and maintenance activities are continued in adverse weather during maintenance periods is that, when repair activities are performed in adverse weather the components are exposed to increased stress levels which in turn increases the frequency of component outages. The interruption duration is reduced by the early restoration of the components. Hence, in order to provide a higher reliability level to consumers, utilities must consider preventive maintenance programs in their design activities. The decision as to whether repairs are to continued in adverse weather depends solely on the requirements of the consumer (e.g., shorter interruption rates may be more important than a lower reliability level).

7.5 Transients

In power system terminology, transient interruptions are referred to as an increase in voltage levels of less than half a cycle [23]. In Chapter VI, the impacts of transient interruptions on the load points' reliability indices of the IEEE 14 bus power system were studied. It was found that the average duration of load point interruptions was very small when compared to the results excluding transient outages; whereas the frequency of interruptions of the electrical power supply were much higher. Since transients cannot be eliminated entirely, equipment/devices (e.g., motor generator set, transient suppressor, power conditioners, UPS, etc.) can be used at the load centers to reduce the impact of transient disturbances.

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APPENDIX A

Bidirectional Components Example

The flow graph method for finding the operational paths to load points described in Chapter II is applied to a network with bidirectional components. Consider the following figure.

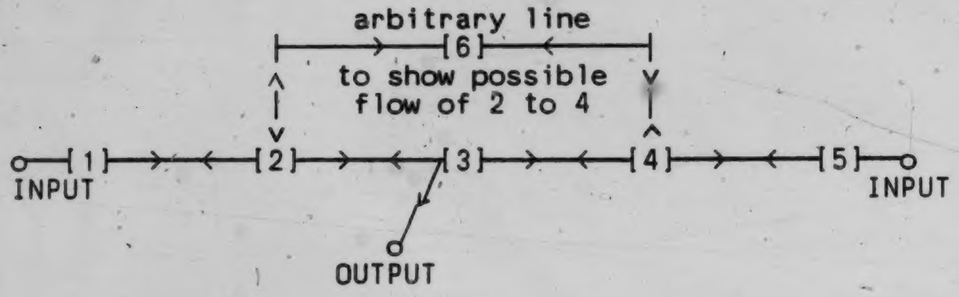

Figure A.1 Bidirectional components network.

The combinations of the components for the above figure are as shown below. Note that for each order there are m! more combinations than the unidirectional network.

Table A.1 All possible combinations for the figure above.

Combination order	Combinations
1st (6 terms)	1, 2, 3, 4, 5, 6
2nd (30 terms)	1-2, 1-3, 1-4, 1-5, 1-6, 2-1, 2-3, 2-4, 2-5, 2-6, 3-1, 3-2, 3-4, 3-5, 3-6, 4-1, 4-2, 4-3, 4-5, 4-6, 5-1, 5-2, 5-3, 5-4, 5-6, 6-1, 6-2, 6-3, 6-4, 6-5.
3rd (120 terms)	1-2-3, 1-2-4, 1-2-5, 1-2-6, 1-3-2, 1-3-4, 1-3-5, 1-3-6, 1-4-2, 1-4-3, 1-4-5, 1-4-6, 1-5-2, 1-5-3, 1-5-4, 1-5-6, 2-1-3, 2-1-4, 2-1-5, 2-1-6, 2-3-1, 2-3-4, 2-3-5, etc.

Table A.1 cont.

4th (360 terms)	1-2-3-4, 1-2-3-5, 1-2-3-6, 1-2-4-3, 1-2-4-5, 1-2-4-6, 1-2-5-3, 1-2-5-4, 1-2-5-6, 1-2-6-3, 1-2-6-4, 1-2-6-5, 1-3-2-4, 1-3-2-5, 1-3-2-6, 1-3-4-2, 1-3-4-5, 1-3-4-6, 1-3-5-2, 1-3-5-4, 1-3-5-6, 1-3-6-2, 1-3-6-4, 1-3-6-5, 1-4-2-3, 1-4-2-5, 1-4-2-6, 1-4-3-2, 1-4-3-2, 1-4-3-5, 1-4-3-6, 1-4-5-2, 1-4-5-3, 1-4-5-6, 1-4-6-2, 1-4-6-3, 1-4-6-5, 1-5-2-3, 1-5-2-4, 1-5-2-6, 1-5-3-2, 1-5-3-4, 1-5-3-6, 1-5-4-2, 1-5-4-3, 1-5-4-6, 1-5-6-2, 1-5-6-3, 1-5-6-4, 1-6-2-3, 1-6-2-4, 1-6-2-5, 1-6-3-2, 1-6-3-4, 1-6-3-5, 1-6-4-2, 1-6-4-3, 1-6-4-5, 1-6-5-2, 1-6-5-3, 1-6-5-4, 2-1-3-4, 2-1-3-5, 2-1-3-6, etc.
5th (720 terms)	1-2-3-4-5, 1-2-3-4-6, 1-2-3-5-4, 1-2-3-5-6, 1-2-4-3-5, 1-2-4-3-6, 1-2-4-5-3, 1-2-4-5-6, 1-2-5-3-4, 1-2-5-3-6, 1-2-5-4-3, 1-2-5-4-6, 1-2-6-3-4, 1-2-6-3-5, 1-3-2-4-5, 1-3-2-4-6, 1-3-2-5-4, 1-3-4-2-6, 1-3-4-2-5, 1-3-4-2-6, 1-3-4-5-2, 1-3-4-5-6, 1-3-5-2-4, 1-3-5-4-2, 1-3-5-4-6, 1-3-6-2-4, 1-3-6-2-5, 1-3-6-4-2, 1-3-6-4-5, 1-3-6-5-2, 1-3-6-5-4, 1-4-2-3-5, 1-4-2-3-6, 1-4-2-5-3, 1-4-2-5-6, 1-4-3-2-5, 1-4-3-2-6, 1-4-3-5-2, 1-4-3-5-6, 1-4-3-6-2, 1-4-3-6-5, 1-4-5-2-3, 1-4-5-2-6, 1-4-5-3-2, 1-4-5-3-6, 1-4-5-6-2, 1-4-5-6-3, 1-4-6-2-3, 1-4-6-2-5, 1-4-6-3-2, 1-4-6-3-5, 1-4-6-5-2, 1-4-6-5-3, 1-5-2-3-4, 1-5-2-3-6, 1-5-2-4-3, 1-5-2-4-6, etc.
6th (720 terms)	1-2-3-4-5-6, 1-2-3-4-6-5, 1-2-3-5-4-6, 1-2-3-5-6-4, 1-2-3-6-4-5, 1-2-3-6-5-4, 1-2-4-3-5-6, 1-2-4-3-6-5, etc.

The combinations that form successful operational paths are :

– 1-2-3, 5-4-3, 1-2-6-4-3, 5-4-6-2-3 .

APPENDIX B

Figure B.1 The numbering order of the distribution network configuration of Figure 5.1, i.e., The University of Alberta power distribution system.

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APPENDIX C

Table C.1 The ACE(i,j) array of the the University of Alberta distribution network configuration.

Element #	Adjacent Connecting Elements			Element #	Adjacent Connecting Elements		
1	-1	3	6	2	1		
3	49			4	1		
5	1			6	1	13	
7	13			8	13		
9	13			10	13		
11	14			12	14		
13	-1	6		14	10		
15	-1	19		16	15		
17	15			18	15		
19	15	32		20	32		
21	32			22	32		
23	32			24	32	34	
25	34			26	34		
27	34			28	36		
29	36			30	15		
31	15			32	-1	19	24
33	34			34	-1	24	
35	36			36	27		
37	16			38	28		
39	20			40	30		
41	31			42	33		
43	35			44	-1		
45	44			46	45		
47	46			48	47		
49	48			50	4	61	
51	7	62		52	2	452	
53	11	453		54	5	820	
55	8	454		56	9	821	
57	17	841		58	22	319	
59	25	314		60	26	442	
61	50	63		62	51	65	
63	61	69		64	62	75	
65	61			66	62		
67	65			68	66		
69	63	177		70	67		
71	68			72	74	75	
73	76	177		74	72	77	
75	64	72		76	73	78	
77	74	79		78	76	204	306
79	77	205	307	80	71		
81	70			82	81		

Table C.1 cont.

Element #	Adjacent Connecting Elements	Element #	Adjacent Connecting Elements
83	80	84	72
85	177	86	84
87	85	88	82
89	83	90	82
91	83	92	82
93	83	94	82
95	86	96	87
97	86	98	87
99	86	100	87
101	88	102	89
103	90	104	91
105	92	106	93
107	94	108	95
109	96	110	97
111	98	112	99
113	100	114	101
115	102	116	103
117	104	118	105
119	106	120	107
121	136	122	108
123	109	124	110
125	111	126	112
127	113	128	114
129	115	130	116
131	117	132	118
133	457	134	119
135	120	136	151
137	122	138	123
139	124	140	125
141	126	142	127
143	141 142	144	143
145	144	146	147
147	140 161	148	139 161
149	138 162	150	137 162
151	135 165	152	134 165
153	130 131	154	129 166
155	128 166	156	147
157	147	158	156
159	146	160	157
161	147 148	162	150 149
163	188	164	191
165	151 152	166	154 155
167	170	168	173
169	176	170	158
171	167	172	171
173	159	174	168
175	174	176	160

Table C.1 cont.

Element #	Adjacent Connecting Elements	Element #	Adjacent Connecting Elements
177	69 73	178	169
179	178	180	148
181	180	182	149
183	182	184	150
185	184	186	121
187	186	188	151
189	163	190	189
191	151	192	164
193	192	194	152
195	194	196	195
197	132	198	153
199	198	200	154
201	200	202	155
203	202	204	78 206
205	79 207	206	204 208
207	205 209	208	206 210
209	107 211	210	208 212
211	209 213	212	210 214
213	211 215	214	212 221
215	213 222	216	209
217	208	218	222
219	221	220	222 309
221	214 223	222	215 220
223	221 308	224	216
225	217	226	219
227	218	228	224
229	225	230	224
231	225	232	224
233	225	234	226
235	227	236	226
237	227	238	228
239	229	240	230
241	231	242	232
243	233	244	234
245	235	246	236
247	237	248	238
249	239	250	240
251	241	252	242
253	243	254	244
255	245	256	247
257	248	258	249
259	250	260	251
261	252	262	253
263	254	264	255
265	288	266	256
267	456	268	266
269	455	270	265

Table C.1 cont.

Element #	Adjacent Connecting Elements	Element #	Adjacent Connecting Elements
271	264 281	272	263 281
273	262	274	259 260
275	258 305	276	257 305
277	271	278	277
279	272	280	279
281	271 272	282	273
283	273	284	282
285	283	286	284
287	286	288	246
289	285	290	289
291	456	292	261
293	274	294	274
295	293	296	294
297	295	298	296
299	297	300	298
301	275	302	301
303	276	304	303
305	275 276	306	78 450
307	79 451	308	223 310
309	220 323	310	308 312
311	318 313	312	310 314
313	311 315	314	312 59
315	312 316	316	315 18
317	21 441	318	311 320
319	321 58	320	318 322
321	319 323	322	320 324
323	321 309	324	322 439
325	322	326	321
327	312	328	313
329	326	330	325
331	328	332	327
333	329	334	330
335	329	336	330
337	332	338	331
339	332	340	331
341	332	342	331
343	332	344	331
345	333	346	334
347	335	348	336
349	337	350	338
351	339	352	340
353	341	354	342
355	343	356	344
357	345	358	346
359	347	360	348
361	349	362	350
363	351	364	352

Table C.1 cont.

Element #	Adjacent Connecting Elements	Element #	Adjacent Connecting Elements
365	353	366	354
367	355	368	356
369	357	370	358
371	359	372	360
373	361	374	362
375	363	376	364
377	365	378	366
379	367	380	368
381	369	382	370 381
383	371 398	384	372 398
385	373 407	386	374 407
387	375 408	388	376 408
389	377 409	390	378 409
391	379 410	392	380 410
393	382	394	393
395	383	396	455
397	395	398	383 384
399	384	400	384
401	399	402	400
403	401	404	403
405	402	406	405
407	385 386	408	387 388
409	389 390	410	391 392
411	430	412	429
413	428	414	427
415	385	416	415
417	386	418	417
419	387	420	419
421	388	422	421
423	389	424	423
425	390	426	425
427	391	428	391
429	392	430	392
431	414	432	431
433	413	434	433
435	412	436	435
437	411	438	437
439	324 468	440	443 465
441	317 455	442	60 456
443	440 455	444	455 477
445	456 478	446	457 475
447	458 476	448	459 471
449	460 472	450	306 459
451	307 460	452	52 461
453	53 462	454	55 463
455	441 443 444	456	442 445
457	446 466	458	447 468

Table C.1 cont.

Element #	Adjacent Connecting Elements	Element #	Adjacent Connecting Elements
459	448 450	460	449 451
461	452 464	462	453 1199
463	454 465	464	461 469
465	440 463	466	457 477
467	458 478	468	439 458
469	464 825	470	824 1199
471	448 473	472	449 474
473	471 475	474	472 476
475	446 473	476	447 474
477	444 466	478	445 467
479	474 910	480	473 911
481	458	482	459
483	460	484	461
485	462	486	463
487	463	488	489
489	463	490	489
491	488	492	486
493	484	494	487
495	485	496	482
497	483	498	133
499	481	500	269
501	291	502	396
503	267	504	490
505	494	506	494
507	492	508	491
509	494	510	492
511	494	512	492
513	494	514	492
515	494	516	492
517	495	518	493
519	195	520	493
521	491	522	496
523	497	524	496
525	497	526	496
527	497	528	496
529	497	530	496
531	497	532	499
533	498	534	498
535	499	536	498
537	500	538	501
539	500	540	501
541	500	542	501
543	502	544	503
545	502	546	503
547	502	548	503
549	502	550	503
551	502	552	504

Table C.1 cont.

Element #	Adjacent Connecting Elements	Element #	Adjacent Connecting Elements
553	505	554	506
555	507	556	508
557	509	558	510
559	511	560	512
561	513	562	514
563	515	564	516
565	517	566	518
567	519	568	520
569	521	570	522
571	523	572	524
573	525	574	526
575	527	576	528
577	529	578	530
579	531	580	532
581	533	582	534
583	535	584	536
585	537	586	538
587	539	588	540
589	541	590	542
591	543	592	544
593	545	594	546
595	547	596	548
597	549	598	550
599	551	600	552
601	553	602	554
603	555	604	556
605	557	606	558
607	559	608	560
609	561	610	562
611	563	612	564
613	565	614	566
615	567	616	568
617	569	618	703 704
619	705 706	620	707 708
621	709 710	622	711 712
623	713 714	624	715 716
625	717 718	626	570
627	571	628	572
629	573	630	574
631	721 722	632	575
633	576	634	723 724
635	577	636	578
637	579	638	580
639	581	640	582
641	583	642	584
643	585	644	586
645	587	646	588

Table C.1 cont.

Element #	Adjacent Connecting Elements	Element #	Adjacent Connecting Elements
647	589	648	590
649	591	650	592
651	593	652	594
653	595	654	596
655	597	656	598
657	599	658	733 734
659	730 731	660	728 729
661	726 727	662	600
663	601	664	602
665	603	666	605
667	606	668	607
669	608	670	609
671	610	672	611
673	612	674	613
675	614	676	615
677	626	678	627
679	628	680	629
681	630	682	632
683	633	684	635
685	636	686	637
687	641	688	642
689	643	690	644
691	645	692	646
693	647	694	648
695	649	696	650
697	651	698	652
699	653	700	654
701	655	702	656
703	618 662	704	618 663
705	619 664	706	619 665
707	620 666	708	620 667
709	621 668	710	621 668
711	622 670	712	622 671
713	623 672	714	623 673
715	624 674	716	624 675
717	625 676	718	625 1202
719	677 678	720	679 680
721	631 681	722	631 682
723	634 683	724	634 684
725	635 686	726	661 687
727	661 688	728	660 689
729	660 690	730	659 691
731	659 692	732	693 694
733	658 695	734	658 696
735	697 698	736	699 700
737	701 702	738	703
739	704	740	705

Table C.1 cont.

Element #	Adjacent Connecting Elements	Element #	Adjacent Connecting Elements
741	706	742	604
743	707	744	708
745	709	746	710
747	711	748	712
749	713	750	714
751	715	752	716
753	717	754	718
755	617	756	719
757	720	758	721
759	722	760	723
761	724	762	725
763	638	764	639
765	640	766	726
767	727	768	728
769	729	770	730
771	731	772	732
773	733	774	734
775	735	776	736
777	737	778	657
779	778	780	777
781	776	782	775
783	774	784	773
785	772	786	771
787	770	788	769
789	768	790	767
791	766	792	765
793	764	794	763
795	762	796	761
797	760	798	759
799	758	800	757
801	756	802	755
803	754	804	753
805	752	806	751
807	750	808	749
809	748	810	747
811	746	812	745
813	744	814	743
815	742	816	741
817	740	818	739
819	738	820	54 1200
821	56 1201	822	898 975
823	899 976	824	470 1203
825	469 1204	826	1203 1205
827	1204 1206	828	896 977
829	897 978	830	896 1205
831	897 1206	832	896 979
833	897 980	834	894 979

Table C.1 cont.

Element #	Adjacent Connecting Elements	Element #	Adjacent Connecting Elements
835	895 980	836	894 981
837	895 982	838	892 981
839	893 982	840	892 1198
841	57 893	842	899
843	898	844	1204
845	1203	846	1204
847	1203	848	897
849	896	850	895
851	894	852	893
853	892	854	900
855	901	856	900
857	901	858	900
859	901	860	900
861	902	862	903
863	902	864	903
865	902	866	903
867	902	868	903
869	902	870	903
871	904	872	905
873	904	874	905
875	904	876	905
877	904	878	905
879	904	880	905
881	906	882	907
883	906	884	907
885	906	886	909
887	908	888	909
889	908	890	909
891	908	892	838 840
893	839 841	894	834 836
895	835 837	896	828 832 830
897	829 833 831	898	822 912
899	823 913	900	843
901	842	902	845 847
903	844 846	904	849
905	848	906	850
907	851	908	853
909	852	910	479 1200
911	480 1201	912	898 977
913	899 978	914	1055
915	1056	916	1064 1065
917	1057	918	1063 1066
919	1052	920	1049
921	1067 1068	922	1068
923	1068 1069	924	1047
925	1046	926	1044
927	1070 1071	928	1042

Table C.1 cont.,

Element #	Adjacent Connecting Elements	Element #	Adjacent Connecting Elements
929	1040	930	1072 1073
931	1038	932	1036
933	1074 1075	934	1034
935	1032	936	1076 1077
937	1030	938	1028
939	1078 1079	940	1026
941	1024	942	1080 1081
943	1022	944	1021
945	1020	946	1019
947	1018	948	1015
949	1014	950	1011
951	1010	952	1008
953	1006	954	1000
955	1085 1086	956	999
957	1103	958	998
959	997	960	1087
961	1101	962	996
963	1087	964	1005
965	1099	966	989
967	1088 1089	968	988
969	987	970	1090 1091
971	986	972	985
973	984	974	983
975	822 1200	976	823 1201
977	828 912	978	829 913
979	832 834	980	833 835
981	836 838	982	837 839
983	1207	984	891
985	890	986	889
987	888	988	887
989	886	990	966
991	968	992	969
993	971	994	972
995	973	996	885
997	884	998	883
999	882	1000	881
1001	954	1002	956
1003	959	1004	962
1005	1087	1006	880
1007	953	1008	879
1009	952	1010	878
1011	877	1012	950
1013	951	1014	876
1015	875	1016	948
1017	949	1018	874
1019	873	1020	872
1021	871	1022	870

Table C.1 cont.

Element #	Adjacent Connecting Elements	Element #	Adjacent Connecting Elements
1023	943	1024	869
1025	941	1026	868
1027	940	1028	867
1029	938	1030	866
1031	937	1032	865
1033	935	1034	864
1035	934	1036	963
1037	932	1038	862
1039	931	1040	861
1041	929	1042	860
1043	928	1044	859
1045	926	1046	858
1047	857	1048	924
1049	856	1050	920
1051	855	1052	1209
1053	919	1054	854
1055	1208	1056	1208
1057	1209	1058	917
1059	915	1060	914
1061	945	1062	944
1063	918 1060	1064	916 1059
1065	916 1058	1066	918 1053
1067	921 1050	1068	921 923
1069	923 1048	1070	927 1045
1071	927 1043	1072	930 1041
1073	930 1039	1074	933 1037
1075	933 1035	1076	936 1033
1077	936 1031	1078	939 1029
1079	939 1027	1080	942 1025
1081	942 1023	1082	1016 1017
1083	1012 1013	1084	1007 1009
1085	955 1001	1086	955 1002
1087	1003 1004	1088	967 990
1089	967 991	1090	970 992
1091	970 993	1092	994 995
1093	974	1094	1092
1095	1091	1096	1090
1097	1089	1098	1088
1099	964	1100	963
1101	960	1102	958
1103	1086	1104	1085
1105	1084	1106	1083
1107	1082	1108	1082
1109	947	1110	946
1111	1081	1112	1080
1113	1079	1114	1078
1115	1077	1116	1076

Table C.1 cont.

Element #	Adjacent Connecting Elements	Element #	Adjacent Connecting Elements
1117	1075	1118	1074
1119	1073	1120	1072
1121	1071	1122	1070
1123	925	1124	1069
1125	922	1126	1067
1127	1066	1128	1065
1129	1064	1130	1063
1131	1130	1132	1129
1133	1127	1134	1126
1135	1125	1136	1124
1137	1123	1138	1122
1139	1121	1140	1120
1141	1119	1142	1118
1143	1117	1144	1116
1145	1115	1146	1114
1147	1113	1148	1112
1149	1111	1150	1110
1151	1109	1152	1108
1153	1107	1154	1106
1155	1105	1156	1104
1157	957	1158	1102
1159	961	1160	1100
1161	965	1162	1098
1163	1097	1164	1096
1165	1095	1166	1061
1167	1062	1168	1175 1188
1169	1176 1188	1170	1175
1171	1175	1172	1175
1173	1176	1174	1176
1175	1166 1168	1176	1167 1169
1177	1193	1178	1177
1179	1192	1180	1191
1181	1190	1182	1189
1183	1178	1184	1179
1185	1180	1186	1181
1187	1182	1188	1168 1169
1189	1170	1190	1171
1191	1172	1192	1173
1193	1174	1194	40
1195	41	1196	43
1197	42	1198	23 840
1199	462 470	1200	820 910 975
1201	821 911 975	1202	616
1203	824 826	1204	825 827
1205	826 830	1206	827 831
1207	909	1208	1054
1209	1051	1210	1128

Table C.1 cont.

Element #	Adjacent Connecting Elements	Element #	Adjacent Connecting Elements
1211	1094	1212	1093

APPENDIX D

The following equations are necessary in order to understand the reliability indices (such as availability, failure/outage rates and durations) presented in this thesis. Note that a power system network can be regarded as a group of series and parallel subsystems which are interconnected.

D.1 Basic Probability Concepts

1. Probability of system or operational success

$$= P(\text{ favourable outcome })$$

$$= \frac{\text{Duration of favorable outcomes}}{\text{Duration of favorable and unfavorable outcomes}}$$

2. Probability of the occurrence of EITHER A OR B OR BOTH, where A and B are two separate events is:

$$= P(A \cup B)$$

$$= P(A) + P(B) - P(A \cap B)$$ ---(iff A and B are not mutually exclusive)

$$= P(A) + P(B)$$ ---(iff A and B are mutually exclusive since $P(A \cap B) = 0$)

3. Probability of occurrence of both A and B

$$= P(A \cap B)$$

$$= P(A) * P(B)$$ ---(iff A and B are independent)

$$\Rightarrow P(A \cup B) = P(A) + P(B) - P(A) * P(B)$$ ---(A & B are independent but not mutually exclusive)

4. Probability of failure + Probability of success = 1.0

   $P(A) + P(\bar{A}) = 1.0$

5. The number of ways that exactly r success and (n-r) failures can occur in n trials is nCr, where

$$nCr = \frac{n!}{r!\,(n-r)!}$$

6. The reliability problem normally deals with systems that are discrete in space and continuous in time. If a system or a component is characterized by an exponential failure density functions then the conditional probability of failure during any fixed interval is constant [13]. The power system problem is normally concerned with system or components that are repairable rather than those which are non-repairable. Consider the case of a single repairable component for which the failure and repair rates are characterized by an exponential distributions.

Define:

$P_0(t)$ = Probability that the component is operable at time t

$P_1(t)$ = Probability that the component failed at time t

λ = failure rate

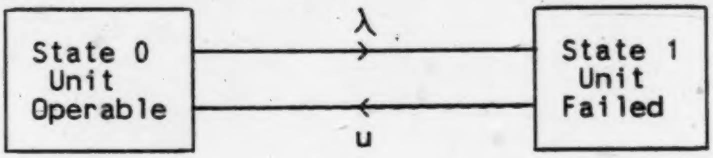
r = repair time = 1/u

Consider an increment time interval dt and assume that the probability of two or more events occuring during this increment of time is negligible.

$$P_0(t + dt) = P_0(t) * (1 - \lambda dt) + P_1(t) * (u\,dt)$$

$$P_1(t + dt) = P_1(t) * (1 - u\,dt) + P_0(t) * (\lambda dt)$$

The state space diagram for this simple system is as follows:



From the above equations

$$\{ P_0(t + dt) - P_0(t) \} / dt = - \lambda P_0(t) + u P_1(t)$$

$$= dP_0(t) /dt = P'_0(t)$$

as t --> 00

In matrix form

$$\begin{bmatrix} P'_0(t) & P'_1(t) \end{bmatrix} = \begin{bmatrix} P_0(t) & P_1(t) \end{bmatrix} \begin{bmatrix} -\lambda & \lambda \\ u & -u \end{bmatrix}$$

Solving for $P_0(t)$ and $P_1(t)$ with initial conditions

- $P_0(t=0) = 1.0$ (i.e., system in operating condition at time zero)
- $P_1(t=0) = 0.$

the following equation are obtained:

$$P_0(t) = \frac{u}{\lambda + u} + \frac{\exp[-(\lambda + u)t]}{\lambda + u}$$

$$P_1(t) = \frac{\lambda}{\lambda + u} - \frac{\exp[-(\lambda + u)t]}{\lambda + u}$$

As t --> OO , i.e., in steady state

$$P_0(t) = \frac{u}{\lambda + u} \quad ; \quad P_1(t) = \frac{\lambda}{\lambda + u} \quad .$$

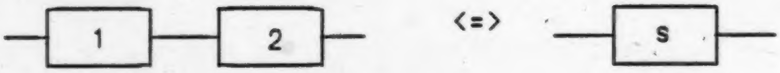
7. The frequency of encoutering a state is given by

$$f = (\text{Probability of encountering the state}) * (\text{Rate of Departure from that state})$$

For the state space diagram in (6.) the frequency is

$$f = \lambda P_0 = u P_1$$

8. Series system - if two components in series are to be represented by a single model characterized by repair and failure parameters, the probabilities asoociated with the operating state must be equal.



$$\underline{P} = \frac{u1}{(\lambda1 + u1)} \; \frac{u2}{(\lambda2 + u2)} \iff \frac{us}{(\lambda s + us)}$$

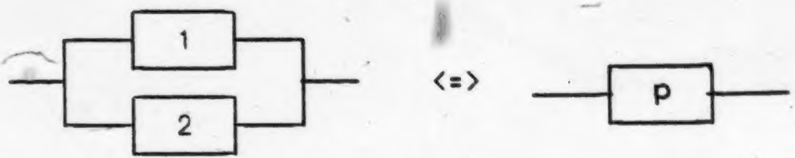
$$\lambda = \lambda1 + \lambda2 \iff \lambda s$$

$$r = \frac{\lambda1\ r1 + \lambda2\ r2 + \lambda1\ \lambda2\ r1\ r2}{\lambda s} \iff rs = 1/\ us$$

$$\approx [\ \lambda1\ r1 + \lambda2\ r2\ ] \ / \lambda s$$

(generally, $\lambda1\,\lambda2$ r1 r2 is much smaller than 1 r1 and 2 r2)

9. Parallel system - in the case of two compoenents in parellel, an equivalent single component model can also be obtained. If the assumption is made that the system is completely redundant, the system will fails only when both components fail.



$$P_f = \frac{\lambda 1}{(\lambda 1 + u1)} \; \frac{\lambda 2}{(\lambda 2 + u2)} \quad <=> \quad \frac{\lambda p}{(\lambda p + up)}$$

$$u = u1 + u2 \quad <=> \quad up$$

$$r = 1/\,up = \frac{r1 + r2}{r1\ r2} \quad <=> \quad rp$$

$$\lambda = \frac{\lambda 1\, \lambda 2\ (r1 + r2)}{\lambda 1 + \lambda 1\ r1 + \lambda 2\ r2} \quad <=> \quad \lambda p$$

10. General equiavalent model parameters for n components

Model	Series system	Parallel system
Failure rate,	$\lambda_s = \sum_{i=1}^{n} \lambda_i$	$\lambda_p = \frac{\left[(\prod_{i=1}^{n} \lambda_i)(\sum_{i=1}^{n} u_i) \right]}{\left[[\prod_{i=1}^{n} (\lambda_i + u_i)] - \prod_{i=1}^{n} \lambda_i \right]}$
Average repair time, r	$r_s = \frac{[\prod_{i=1}^{n} (1 + \lambda_i\, r_i) - 1]}{\lambda_s}$	$r_p = 1/\,u_p$ $u_p = \sum_{i=1}^{n} u_i$

D.2.1 Definitions of necessary data

1. A normal weather (random) "permanent" forced outage rate should be estimated for all types of apparatus and lines which exhibit distinctive failure rates. This failure rate (λ) is expressed in units of failures per year of normal weather per unit of apparatus or mile of line. It can be estimated as follows:

$$\lambda = \frac{\text{(number of component failures in normal weather during observation period)}}{\text{(total normal weather exposure time for each mile of line or piece of apparatus during observation period)}}$$

$$= C / Y$$

2. A stormy weather "permanent" forced outage should be obtained from components whose failure rate is affected by weather and which are used in portion of the system, such as the subtransmission system, which is usually operate as a parallel system. The units in this case is failures per year of stormy weather per mile of line or per unit of apparatus. The estimate is

$$\lambda_s = \frac{\text{(number of component failures in stormy weather during observation period)}}{\text{(total stormy weather exposure time for each mile of line or piece of apparatus during observation period)}}$$

$$= Cs / Ys$$

3. Maintenance outage rates should be obtained for types of components which are used in portions of the system which operate as a parallel system. Maintenance outages

of components in radial systems, if such occur, can be combined together with the normal weather forced outages. Maintenance outage rate (λm) has the units of outages per year per unit of apparatus or per mile of line. It may be estimated by

$$\lambda_m = \frac{\text{(number of component maintenance outages during observation period)}}{\text{(total observation periods for each line or piece of apparatus (exposure to maintenance is assumed to be essentially the same each each year))}}$$

$$= Cm \,/\, Ym$$

4. A temporary forced outage (transient) rate for various types of components is necessary if system temporary outages are to be calculated. In general, a temporary outages does not require repair or replacement of facilities but can be remedied by a reclosing operation or by replacing a fuse. Component temporary outage is estimated by

$$\lambda_t = \frac{\text{(number of component temporary outages)}}{\text{(number of years of component exposure)}}$$

$$= Ct \,/\, Yt$$

5. Repair times are generally obtained from historical records. It is defined as the duration of a period during which a component is out of service being repaired or replaced following a forced outage, or the time a component is out of service for maintenance or other work. Repair time distributions seem to be

exponential to a reasonable approximation. That is,

$$P(\text{ repair time, } r > t) = \exp(-t/r)$$

r = expected repair time for all forced outages, unit is in years

r" = expected down time for maintenance outages, unit is in years.

6. N = expected value of normal weather period duration, unit - in years.

7. S = expected value of stormy weather period duration, unit - in years.

D.2.2 Assumptions

1. Times to failure and repair times are exponentially distributed, in both normal and stormy weather.
2. The durations of periods of normal and stormy weather are exponential distributed.
3. Storms are very short in duration compared with times to failure and repair of components.
4. Maintenance outages occur at random during normal weather periods except that components are not taken out for maintenance if
   - (i) such action would cause the remaining components in a parallel system to become overloaded,
   - (ii) maintenance could not be completed before a storm struck.
5. Maintenance down times are exponentially distributed.

D.2.3 Equations to determine outage rates and durations

The following equations were used to caluculate the outage rates and outage durations associated with first, second and third order cut sets. Equations for higher order cut sets can be written in a similar manner [15,22]. In power system, the approximation equations are usable because the failure rate and repair time of the components in a power system are generally very small and hence the error involve is negligible [16]. Recall that the elements within a cut are connected in parallel, and that all the cut sets are connected in series with one order, i.e., the overall system/consumer failure rate and duration may be found by the general series equation shown in D.1.

Definition of symbols:

λ -- system/consumer failure rate, f/yr

r -- system/consumer repair time, years

λ_i -- normal weather permanent failure rate of component i, f/yr

r_i -- repair rate of component i, years

λ_{si} -- adverse weather permanent failure rate of component i, f/yr

λ_{mi} -- maintenance rate of component i, outage/yr

r_{mi} -- maintenance outage duration of component i, years

λ_{ti} -- normal weather temporary outage rate of component i, f/yr

λ_{sti} -- adverse weather temporary outage duration of component i, f/yr

N -- average normal weather outage duration, years

S -- average adverse weather outage duration, years

1. PERMANENT OUTAGES

1.1 Weather Independent

These are the equations used for reliability indices evaluation in Chapter III, which can be easily obtained from the general equations for series-parallel system discribed in D.1 .

(a) first order cut set

$$\lambda = \lambda_i$$

$$r = r_i$$

where: i is the component contained in the 1st order cut set.

(b) second order cut set

$$\lambda = \frac{\lambda_i\lambda_j\ (r_i + r_j)}{1 + \lambda_i r_i + \lambda_j r_j}$$

$$= \lambda_i\lambda_j\ (r_i + r_j)$$

$$r = \frac{r_i r_j}{r_i + r_j}$$

where: i and j are the components contained in the 2nd order cut set.

(c) third order cut set

$$\lambda = \frac{\lambda_i\lambda_j\lambda_k\ (r_i r_j + r_i r_k + r_j r_k)}{1+\lambda_i r_i+\lambda_j r_j+\lambda_k r_k+\lambda_i\lambda_j r_i r_j+\lambda_i\lambda_k r_i r_k+\lambda_j\lambda_k r_j r_k}$$

$$= \lambda_i\lambda_j\lambda_k\ (r_i r_j + r_i r_k + r_j r_k)$$

$$r = \frac{r_i r_j r_k}{r_i r_j + r_i r_k + r_j r_k}$$

where: i, j and k are the components contained in the 3rd order cut set.

1.2 Weather Dependent

1.2.1 Repair Activities Continued in Adverse Weather

(a) first order cut set

$$\lambda = \frac{N}{N + S} \lambda_i + \frac{S}{N + S} \lambda_{is}$$

$$r = r_i$$

where: i is the component contained in the 1st order cut set.

(b) second order cut set

$$\begin{aligned}
\lambda = \frac{N}{N + S} \Bigg[& \lambda_i \lambda_j \left(\frac{r_i}{1 + \lambda_j r_i} + \frac{r_j}{1 + \lambda_i r_j} \right) \\
& + \frac{S}{N} \Bigg(\lambda_i \lambda_{js} \frac{r_i^2}{[1 + \lambda_{js} S r_i / (S + r_i)](S + r_i)} \\
& \qquad + \lambda_j \lambda_{is} \frac{r_j^2}{[1 + \lambda_{is} S r_j / (S + r_j)](S + r_j)} \Bigg) \Bigg] \\
+ \frac{S}{N + S} \Bigg[& \lambda_{is} \lambda_j \frac{r_i N}{[1 + \lambda_j r_i N/(N + r_i)](N + r_i)} + \\
& \lambda_{js} \lambda_i \frac{r_j N}{[1 + \lambda_i r_j N/(N + r_j)](N + r_j)} + \\
& S \lambda_{is} \lambda_{js} \Bigg(\frac{r_i}{[1 + \lambda_{js} S r_i / (S + r_i)](S + r_i)} + \\
& \qquad \frac{r_j}{[1 + \lambda_{is} S r_j / (S + r_j)](S + r_j)} \Bigg) \Bigg]
\end{aligned}$$

$$= \frac{N}{N + S} \left[\lambda_i \lambda_j (r_i + r_j) + \frac{S}{N} \left(\lambda_i \lambda_{js} \frac{r_i^2}{S+r_i} + \lambda_j \lambda_{is} \frac{r_i^2}{S+r_i} \right) \right] +$$

$$\frac{S}{N + S} \left[\lambda_{is} \lambda_j \frac{Nr_i}{N+r_i} + \lambda_{js} \lambda_i \frac{Nr_j}{N+r_j} + \lambda_{is} \lambda_{js} S \left(\frac{r_i}{S+r_i} + \frac{r_j}{S+r_j} \right) \right]$$

$$r = \frac{r_i r_j}{r_i + r_j}$$

where: i and j are the components contained in the 2nd order cut set.

(c) third order cut set

$$\lambda = A + B$$

where:

$$A = \frac{N}{N + S} \left[\lambda_i \left(\lambda_j \lambda_k r_i^2 (A_1 + A_2) + \frac{Sr_i^3}{S + r_i} (A_3 + A_4) \right) + \right.$$

$$\left. \text{similar terms for components j and k i.e., i (j k) , then j(k i) and k(i j).} \right]$$

$$+ \frac{S}{N + S} \left[\lambda_{is} \left(\lambda_j \lambda_k \frac{N^2 r_i^2}{N + r_i} (A_5 + A_6) + \frac{NSr_i^2}{S + r_i} (A_7 + A_8) \right) + \right.$$

$$\left. \text{similar terms for components j and k i.e., i(jk), then j(ki) and k(ij).} \right]$$

where:

$$A_1 = \frac{r_j}{(1 + \lambda_j r_i)(r_i + r_j)[1 + \lambda_k r_i r_j/(r_i + r_j)]}$$

$$A_2 = \frac{r_k}{(1 + \lambda_k r_i)(r_i + r_k)[1 + \lambda_j r_i r_k/(r_i + r_k)]}$$

$$A_3 = \frac{\lambda_{js} \lambda_k r_j}{(1 + \lambda_{js} r_i)(1 + \lambda_k N r_i r_j/N_{ij})\ N_{ij}}$$

$$A_4 = \frac{\lambda_{ks} \lambda_j r_i}{(1 + \lambda_{ks} r_i)(1 + \lambda_j N r_i r_k/N_{ik})\ N_{ik}}$$

$$A_5 = \frac{r_j}{(1 + \lambda_j r_i)(N_{ij})[1 + \lambda_k N r_i r_j/N_{ij}]}$$

$$A_6 = \frac{r_k}{(1 + \lambda_k r_i)(N_{ik})[1 + \lambda_j N r_i r_k/N_{ik}]}$$

$$A_7 = \frac{\lambda_{js} \lambda_k r_j}{(1 + \lambda_{js} r_i)(N_{ij})[1 + \lambda_k N r_i r_j/N_{ij}]}$$

$$A_8 = \frac{\lambda_{ks} \lambda_j r_k}{(1 + \lambda_{ks} r_i)(N_{ik})[1 + \lambda_j N r_i r_k/N_{ik}]}$$

$$\begin{aligned} A = \frac{N}{N + S} \Biggl[& \lambda_i \left(\lambda_j \lambda_k r_i^{2} \left(\frac{r_j}{r_i + r_j} + \frac{r_k}{r_i + r_k} \right) \right) \\ & + \left(\lambda_{js} \lambda_k \frac{r_j}{N r_i + N r_j + r_i r_j} + \right. \\ & \left. \lambda_{ks} \lambda_j \frac{r_k}{N r_i + N r_k + r_i r_k} \right) \frac{S r_i^{3}}{S + r_i} \\ & + \text{similar terms for components } j \text{ and } k, \\ & \quad \text{i.e., } i(jk) \text{ then } j(ki) \text{ and } k(ij). \Biggr] \end{aligned}$$

$$+ \frac{S}{N + S} \left[\lambda_{is} \left(\lambda_j \lambda_k \frac{N^2 r_i^2}{N+r_i} \left(\frac{r_j}{Nr_i+Nr_j+r_ir_j} + \frac{r_k}{Nr_i+Nr_k+r_ir_k} \right) \right) + \right.$$

$$\frac{NSr_i^2}{S + r_i} \left(\lambda_{js} \lambda_k \frac{r_j}{Nr_i+Nr_j+r_ir_j} + \lambda_{ks} \lambda_j \frac{r_k}{Nr_i+Nr_k+r_ir_k} \right)$$

+ similar terms for components j and k, i.e., i(jk) then j(ki) and k(ij). $\Big]$

and

$$B = \frac{N}{N + S} \left[\lambda_i \left(\lambda_{js} \lambda_{ks} \frac{S^2 r_i^3}{(S + r_i)N} (B_1 + B_2) + \frac{r_i^3}{N} (B_3 + B_4) \right) + \right.$$

similar terms for components j and k i.e., i(jk), then j(ki) and k(ij). $\Big]$

$$+ \frac{S}{N + S} \left[\lambda_{is} \left(\lambda_{js} \lambda_{ks} \frac{S^2 r_i^2}{S + r_i} (B_5 + B_6) + \frac{r_i^3 NS}{N + r_i} (B_7 + B_8) \right) + \right.$$

similar terms for components j and k i.e., i(jk), then j(ki) and k(ij). $\Big]$

where:

$$B_1 = \frac{r_j}{(S_{ij})[1 + \lambda_{js} Sr_i/(S+r_i)][1 + \lambda_{ks} Sr_ir_j/S_{ij}]}$$

$$B_2 = \frac{r_k}{(S_{ik})[1 + \lambda_{ks}Sr_i/(S+r_i)][1 + \lambda_{js}Sr_ir_k/S_{ik}]}$$

$$B_3 = \frac{\lambda_j\lambda_{ks}r_j^{\,2}}{(r_i + r_j)(1 + \lambda_j r_i)[1 + \lambda_{ks}Sr_ir_j/S_{ij}]\,(S_{ij})}$$

$$B_4 = \frac{\lambda_k\lambda_{js}r_k^{\,2}}{(r_i + r_k)(1 + \lambda_k r_i)[1 + \lambda_{js}Sr_ir_k/S_{ik}]\,(S_{ik})}$$

$$B_5 = \frac{r_j}{[1 + \lambda_{js}Sr_i/(S+r_i)](S_{ij})[1 + \lambda_{ks}Sr_ir_j/S_{ij}]}$$

$$B_6 = \frac{r_k}{[1 + \lambda_{ks}Sr_i/(S+r_i)](S_{ik})[1 + \lambda_{js}Sr_ir_k/S_{ik}]}$$

$$B_7 = \frac{\lambda_j\lambda_{ks}r_j^{\,2}}{[1 + \lambda_j Nr_i/(N+r_i)](N_{ij}S_{ij})[1 + \lambda_{ks}Sr_ir_j/S_{ij}]}$$

$$B_8 = \frac{\lambda_k\lambda_{js}r_k^{\,2}}{[1 + \lambda_k Nr_i/(N+r_i)](N_{ik}S_{ik})]1 + \lambda_{js}Sr_ir_k/S_{ik}]}$$

$$B \approx \frac{N}{N+S}\left[\lambda_i\left(\lambda_{js}\lambda_{ks}\frac{S^2r_i^{\,3}}{(S+r_i)N}\left(\frac{r_j}{Sr_i+Sr_j+r_ir_j} + \frac{r_k}{Sr_i+Sr_k+r_ir_k}\right)\right)\right.$$

$$\left. + \frac{r_i^{\,3}S}{N}\left(\frac{\lambda_j\lambda_{ks}r_j^{\,2}}{(r_i+r_j)(Sr_i+Sr_j+r_ir_j)} + \frac{\lambda_k\lambda_{js}r_k^{\,2}}{(r_i+r_k)(Sr_i+Sr_k+r_ir_k)}\right)\right.$$

$$\left. + \text{ similar terms for components } j \text{ and } k, \text{ i.e., } i(jk) \text{ then } j(ki) \text{ and } k(ij).\right]$$

$$+ \frac{S}{N + S} \Bigg[\lambda_{is} \Bigg(\lambda_{js} \lambda_{ks} \; \frac{S^2 r_i^{\,2}}{S + r_i} \Bigg(\frac{r_j}{Sr_i + Sr_j + r_i r_j} + \frac{r_k}{Sr_i + Sr_k + r_i r_k} \Bigg) \Bigg)$$

$$+ \frac{r_i^{\,3} NS}{N + r_i} \Bigg(\frac{\lambda_j \lambda_{ks} r_j^{\,2}}{(Sr_i + Sr_j + r_i r_j)(Nr_i + Nr_j + r_i r_j)} \quad \frac{\lambda_k \lambda_{js} r_k^{\,2}}{(Sr_i + Sr_k + r_i r_k)(Nr_i + Nr_k + r_i r_k)} \Bigg)$$

+ similar terms for components j and k,
i.e., i(jk) then j(ki) and k(ij). $\Bigg]$

and

$$N_{ij} = Nr_i + Nr_j + r_i r_j$$

$$N_{ik} = Nr_i + Nr_k + r_i r_k$$

$$S_{ij} = Sr_i + Sr_j + r_i r_j$$

$$S_{ik} = Sr_i + Sr_k + r_i r_k$$

$$r = \frac{r_i r_j r_k}{r_i r_j + r_i r_k + r_j r_k}$$

where: i, j and k are the components contained in the 3rd order cut set.

1.2.2 Repair Activities Discontinued in Adverse Weather

(a) first order cut set

$$\lambda = \frac{N}{N+S}\lambda_i + \frac{S}{N+S}\lambda_{is}$$

$$r = \frac{\lambda_i N r_i + \lambda_{is} S(S+r_i)}{\lambda_i N + \lambda_{is} S}$$

where: i is the component contained in the 1st order cut set.

(b) second order cut set

$$\lambda = A + B$$

where:

$$A = \frac{N}{N+S}\left[\lambda_i\lambda_j\left(\frac{r_i}{1+\lambda_j r_i} + \frac{r_j}{1+\lambda_i r_j}\right) + \frac{S}{N}\left(\frac{\lambda_i\lambda_{js}r_i}{1+\lambda_{js}S} + \frac{\lambda_j\lambda_{is}r_j}{1+\lambda_{is}S}\right)\right]$$

$$= \frac{N}{N+S}\left[\lambda_i\lambda_j(r_i + r_j) + \frac{S}{N}(\lambda_{is}\lambda_j r_i + \lambda_{js}\lambda_i r_j)\right]$$

and

$$B = \frac{S}{N+S}\left[\frac{\lambda_{js}\lambda_{is}S}{1+\lambda_{js}S} + \lambda_{is}\lambda_j\frac{r_i}{1+\lambda_j r_i} \quad \frac{\lambda_{is}\lambda_{js}S}{1+\lambda_{is}S} + \lambda_{js}\lambda_i\frac{r_j}{1+\lambda_i r_j}\right]$$

$$= \frac{S}{N+S}\left[2\lambda_{is}\lambda_{js}S + \lambda_i\lambda_{js}r_i + \lambda_{is}\lambda_j r_j\right]$$

$$r = \frac{A}{A+B}\left(\frac{r_i r_j}{r_i + r_j}\right) + \frac{B}{A+B}\left(\frac{r_i r_j}{r_i + r_j} + S\right)$$

where: i and j are the components contained in the 2nd order cut set.

(c) third order cut set

$$\lambda = A + B$$

where:

$$\begin{aligned} A = \frac{N}{N+S} \Bigg[\; & \lambda_i \Bigg(\lambda_j \lambda_k r_i^2 \, (A_1 + A_2) \; + \\ & \qquad \frac{S}{N} r_i^2 \, (A_3 + A_4) \Bigg) \; + \\ & \qquad \text{similar terms for components j and k,} \\ & \qquad \text{i.e., i(jk) then j(ki) and k(ij).} \Bigg] \\ + \frac{S}{N+S} \Bigg[\; & \lambda_{is} \Bigg(\lambda_j \lambda_k r_i^2 \, (A_1 + A_2) \; + \; S r_i \, (A_3 + A_4) \Bigg) \\ & \quad + \text{similar terms for components j and k,} \\ & \qquad \text{i.e., i(jk) then j(ki) and k(ij).} \Bigg] \end{aligned}$$

where:

$$A_1 = \frac{r_j}{(r_i + r_j)(1 + \lambda_j r_i)[1 + \lambda_k r_i r_j / (r_i + r_j)]}$$

$$A_2 = \frac{r_k}{(r_i + r_k)(1 + \lambda_k r_i)[1 + \lambda_j r_i r_k / (r_i + r_k)]}$$

$$A_3 = \frac{\lambda_{js} \lambda_k r_j}{(r_i + r_j)(1 + \lambda_{js} S)[1 + \lambda_k r_i r_j / (r_i + r_j)]}$$

$$A_4 = \frac{\lambda_{ks} \lambda_j r_k}{(r_i + r_k)(1 + \lambda_{ks} S)[1 + \lambda_j r_i r_k / (r_i + r_k)]}$$

$$\begin{aligned} A \approx \frac{N}{N+S} \Bigg[\; & \lambda_i \Bigg(\lambda_j \lambda_k r_i^2 \left(\frac{r_j}{r_i + r_j} + \frac{r_k}{r_i + r_k} \right) \Bigg) \\ & \qquad + \frac{S}{N} r_i^2 \left(\lambda_{js} \lambda_k \frac{r_j}{r_i + r_j} + \frac{r_k}{r_i + r_k} \lambda_{ks} \lambda_j \right) \\ & \qquad + \text{similar terms for components j and k,} \\ & \qquad \text{i.e., i(jk) then j(ki) and k(ij).} \Bigg] \end{aligned}$$

$$
\begin{aligned}
&+ \frac{S}{N+S} \Bigg[\lambda_{is} \left(\lambda_j \lambda_k r_i^2 \left(\frac{r_i}{r_i+r_j} + \frac{r_k}{r_i+r_k} \right) \right) \\
&\qquad + S r_i \left(\lambda_{js} \lambda_k \frac{r_j}{r_i+r_j} + \frac{r_k}{r_i+r_k} \lambda_{ks} \lambda_j \right) \\
&\qquad + \text{similar terms for components j and k, i.e., i(jk) then j(ki) and k(ij).} \Bigg]
\end{aligned}
$$

and

$$
\begin{aligned}
B = \frac{N}{N+S} \Bigg[&\lambda_i \left(2 \lambda_{js} \lambda_{ks} \frac{S^2 r_i}{NB_3} + \frac{S r_i^2}{N} (B_1 + B_2) \right) \\
&+ \text{similar terms for components j and k, i.e., i(jk) then j(ki) and k(ij).} \Bigg] \\
+ \frac{S}{N+S} \Bigg[&\lambda_{is} \left(2 \lambda_{js} \lambda_{ks} \frac{S^2}{B_3} + \frac{S}{N} r_i^2 (B_1 + B_2) \right) \\
&+ \text{similar terms for components j and k, i.e., i(jk) then j(ki) and k(ij).} \Bigg]
\end{aligned}
$$

where:

$$B_1 = \frac{\lambda_j \lambda_{ks} r_j}{(r_i+r_j)(1+\lambda_j r_i)(1+\lambda_{ks} S)}$$

$$B_2 = \frac{\lambda_k \lambda_{js} r_k}{(r_i+r_k)(1+\lambda_k r_i)(1+\lambda_{js} S)}$$

$$B_3 = \frac{1}{(1+\lambda_{js} S)(1+\lambda_{ks} S)}$$

$$
\begin{aligned}
B \approx \frac{N}{N+S} \Bigg[&\lambda_i \left(2 \lambda_{js} \lambda_{ks} r_i \frac{S^2}{N} + \frac{S}{N} r_i^2 \left(\frac{\lambda_j \lambda_{ks} r_j}{r_i + r_j} + \frac{\lambda_{js} \lambda_k r_k}{r_i + r_k} \right) \right) \\
&+ \text{similar terms for components j and k, i.e., i(jk) then j(ki) and k(ij).} \Bigg]
\end{aligned}
$$

$$+ \frac{S}{N + S} \left[\lambda_{is} \left(2\, \lambda_{js} \lambda_{ks} S^2 + \frac{S}{N} r_i^2 \left(\frac{\lambda_j \lambda_{ks} r_j}{r_i + r_j} + \frac{\lambda_{js} \lambda_k r_k}{r_i + r_k} \right) \right) \right.$$

$$\left. \begin{array}{l} + \text{ similar terms for components j and k,} \\ \text{i.e., i(jk) then j(ki) and k(ij).} \end{array} \right]$$

$$r = \frac{A}{A + B} \left[\frac{r_i r_j r_k}{r_i r_j + r_i r_k + r_j r_k} \right] + \frac{B}{A + B} \left[\frac{r_i r_j r_k}{r_i r_j + r_i r_k + r_j r_k} + S \right] .$$

where: i, j and k are the components contained in the 3rd order cut set.

2. PERMANENT AND MAINTENANCE OUTAGES

2.1 Weather Independent

(a) first order cut set

$$\lambda_{ML} = \lambda_{im}$$

$$r_{ML} = r_{im}$$

where: i is the components contained in the 1st order cut set.

(b) second order cut set

$$\lambda_{ML} = \frac{\lambda_{im} \lambda_j r_{im}}{1 + \lambda_j r_{im}} + \frac{\lambda_{jm} \lambda_i r_{jm}}{1 + \lambda_i r_{jm}}$$

$$= \lambda_{im} \lambda_j r_{im} + \lambda_{jm} \lambda_i r_{jm}$$

$$r_{ML} = \frac{\lambda_{im} \lambda_j r_{im}^2}{\lambda_{ML} (r_{im} + r_j)(1 + \lambda_j r_{im})} + \frac{\lambda_{jm} \lambda_i r_{jm}^2}{\lambda_{ML} (r_{jm} + r_i)(1 + \lambda_i r_{jm})}$$

where: i and j are the components contained in the 2nd order cut set.

(c) third order cut set

$$\lambda_{ML} = A + B + C$$

where:

$$A = \lambda_{im} r_{im}^{2} \left[\frac{\lambda_j \lambda_k r_j}{(r_{im}+r_j)(1+\lambda_j r_{im})(1+\lambda_k r_{im} r_j/(r_{im}+r_j))} + \frac{\lambda_j \lambda_k r_k}{(r_{im}+r_k)(1+\lambda_k r_{im})(1+\lambda_j r_{im} r_k/(r_{im}+r_k))} \right]$$

$$= \lambda_{im} \lambda_j \lambda_k r_{im}^{2} \left[\frac{r_j}{r_{im}+r_j} + \frac{r_k}{r_{im}+r_k} \right]$$

B and C are similar to A but for components j and k, respectively, i.e., i(jk) then j(ki) and k(ij).

$$r_{ML} = \frac{A}{\lambda_{ML}} \left[\frac{r_{im} r_j r_k}{(r_{im} r_j + r_{im} r_k + r_j r_k)} \right] + \frac{B}{\lambda_{ML}} \left[\frac{r_{jm} r_k r_i}{(r_{jm} r_k + r_{jm} r_i + r_k r_i)} \right] + \frac{C}{\lambda_{ML}} \left[\frac{r_{km} r_i r_j}{(r_{km} r_i + r_{km} r_j + r_i r_j)} \right]$$

where: i, j and k are the components contained in the 3rd order cut set.

2.2 Weather Dependent

2.2.1 Repair and Maintenance Activities Continued in Adverse Weather

(a) first order cut set

$$\lambda_{ML} = \lambda_{im}$$

$$r_{ML} = r_{im}$$

where: i is the component contained in the 1st order cut set.

(b) second order cut set

$$\lambda_{ML} = A + B$$

where:

$$A = \lambda_{im}\lambda_{j} \frac{r_{im}}{1 + \lambda_{j} r_{im}} + \lambda_{im}\lambda_{js} \frac{r_{im}^{2} S}{N(S+r_{im})(A_{1})}$$

where:

$$A_{1} = 1 + \lambda_{js} r_{im} S/(S+r_{im})$$

$$A = \lambda_{im}\lambda_{j} r_{im} + \lambda_{im}\lambda_{js} \frac{r_{im}^{2} S}{N(S + r_{im})}$$

and

$$B = \lambda_{jm}\lambda_{i} \frac{r_{jm}}{1 + \lambda_{i} r_{jm}} + \lambda_{jm}\lambda_{is} \frac{r_{jm}^{2} S}{N(S+r_{jm})(B_{1})}$$

where:

$$B_{1} = 1 + \lambda_{is} r_{jm} S/(S+r_{jm})$$

$$B = \lambda_{jm}\lambda_{i} r_{jm} + \lambda_{jm}\lambda_{is} \frac{r_{jm}^{2} S}{N(S + r_{jm})}$$

$$r_{ML} = \frac{A}{\lambda_{ML}} \frac{r_{im} r_{j}}{r_{im} + r_{j}} + \frac{B}{\lambda_{ML}} \frac{r_{jm} r_{i}}{r_{i} + r_{jm}}$$

where: i and j are the components contained in the 2nd order cut set.

(c) third order cut set

$$\lambda_{ML} = A + B + C$$

where:

$$A = \lambda_{im} \Big[\lambda_{j}\lambda_{k} r_{im}^{2} (A_{1} + A_{2}) + \frac{S}{N} r_{im}^{3} (A_{3} + A_{4}) + S r_{im}^{3} (A_{5} + A_{6}) + \lambda_{js}\lambda_{ks} \frac{S^{2} r_{im}^{3}}{N(S + r_{im})} (A_{7} + A_{8}) \Big]$$

where:

$$A_1 = \frac{r_j}{(r_{im} + r_j)(1 + \lambda_j r_{im})(1 + \lambda_k r_{im} r_j / (r_{im} + r_j))}$$

$$A_2 = \frac{r_k}{(r_{im} + r_k)(1 + \lambda_k r_{im})(1 + \lambda_j r_{im} r_k / (r_{im} + r_k))}$$

$$A_3 = \frac{\lambda_j \lambda_{ks} r_j^2}{(r_{im} + r_j)(1 + \lambda_j r_{im})(S_{ij})(1 + \lambda_{ks} r_{im} r_j S / S_{ij})}$$

$$A_4 = \frac{\lambda_k \lambda_{js} r_k^2}{(r_{im} + r_k)(1 + \lambda_k r_{im})(S_{ik})(1 + \lambda_{js} r_{im} r_k S / S_{ik})}$$

$$A_5 = \frac{\lambda_{js} \lambda_k r_j}{(S + r_{im})(1 + \lambda_{js} S r_{im} / (S + r_{im}))(N_{ij})(1 + \lambda_k r_{im} r_j N / N_{ij})}$$

$$A_6 = \frac{\lambda_{ks} \lambda_j r_k}{(S + r_{im})(1 + \lambda_{ks} S r_{im} / (S + r_{im}))(N_{ik})(1 + \lambda_j r_{im} r_k N / N_{ik})}$$

$$A_7 = \frac{r_j}{(1 + \lambda_{js} S r_{im} / (S + r_{im}))(S_{ij})(1 + \lambda_{ks} S r_{im} r_j / S_{ij})}$$

$$A_8 = \frac{r_k}{(1 + \lambda_{ks} S r_{im} / (S + r_{im}))(S_{ik})(1 + \lambda_{js} S r_{im} r_k / S_{ik})}$$

where:

$$N_{ij} = N r_{im} + N r_j + r_{im} r_j$$

$$N_{ik} = N r_{im} + N r_k + r_{im} r_k$$

$$S_{ij} = S r_{im} + S r_j + r_{im} r_j$$

$$S_{ik} = S r_{im} + S r_k + r_{im} r_k$$

$$A = \lambda_{im}\left[\lambda_j\lambda_k r_{im}^2\left(\frac{r_j}{r_{im}+r_j}+\frac{r_k}{r_{im}+r_k}\right)\right.$$

$$+\frac{S}{N}r_{im}^3\left(\frac{\lambda_j\lambda_{ks}r_j^2}{(r_{im}+r_j)(Sr_{im}+Sr_j+r_{im}r_j)}+\right.$$

$$\left.\frac{\lambda_k\lambda_{js}r_k^2}{(r_{im}+r_k)(Sr_{im}+Sr_k+r_{im}r_k)}\right)$$

$$+\frac{Sr_{im}^3}{S+r_{im}}\left(\frac{\lambda_{js}\lambda_k r_j}{Nr_{im}+Nr_j+r_{im}r_j}+\frac{\lambda_{ks}\lambda_j r_k}{Nr_{im}+Nr_k+r_{im}r_k}\right)$$

$$+\lambda_{js}\lambda_{ks}\frac{S^2r_{im}^3}{N(S+r_{im})}\left(\frac{r_j}{Sr_{im}+Sr_j+r_{im}r_j}+\right.$$

$$\left.\left.\frac{r_k}{Sr_{im}+Sr_k+r_{im}r_k}\right)\right]$$

B and C are similar to A but for components j and k respectively, i.e., i(jk) then j(ki) and k(ij). where i, j, k are the components contained in the 3rd order cut set.

$$r_{ML} = \frac{A}{\lambda_{ML}}\left[\frac{r_{im}r_jr_k}{r_{im}r_j+r_{im}r_k+r_jr_k}\right]+$$

$$\frac{B}{\lambda_{ML}}\left[\frac{r_{jm}r_kr_i}{r_{jm}r_k+r_{jm}r_i+r_kr_i}\right]+$$

$$\frac{C}{\lambda_{ML}}\left[\frac{r_{km}r_ir_j}{r_{km}r_i+r_{km}r_j+r_ir_j}\right]$$

where: i, j and k are the components contained in the 3rd order cut set.

2.2.2 Repair and Maintenance Activities Discontinued in Adverse Weather

(a) first order cut set

$$\lambda_{ML} = \lambda_{im}$$

$$r_{ML} = r_{im}$$

where: i is the component contained in the 1st order cut set.

(b) second order cut set

$$\lambda_{ML} = A + B + C + D$$

where:

$$A = \lambda_{im}\lambda_{j}\,\frac{r_{im}}{1 + \lambda_{j}r_{im}} = \lambda_{im}\lambda_{j}r_{im}$$

$$B = \lambda_{im}\lambda_{js}\,\frac{Sr_{im}}{(1 + \lambda_{js}S)N} = \lambda_{im}\lambda_{js}r_{im}\,\frac{S}{N}$$

$$C = \lambda_{jm}\lambda_{i}\,\frac{r_{jm}}{1 + \lambda_{i}r_{jm}} = \lambda_{jm}\lambda_{i}r_{jm}$$

$$D = \lambda_{jm}\lambda_{is}\,\frac{Sr_{jm}}{(1 + \lambda_{is}S)N} = \lambda_{jm}\lambda_{is}r_{jm}\,\frac{S}{N}$$

$$r_{ML} = \frac{A}{\lambda_{ML}}\,\frac{r_{im}r_{j}}{r_{im} + r_{j}} + \frac{B}{\lambda_{ML}}\left(\frac{r_{im}r_{j}}{r_{im} + r_{j}} + S\right) + \frac{C}{\lambda_{ML}}\,\frac{r_{i}r_{jm}}{r_{i} + r_{jm}} + \frac{D}{\lambda_{ML}}\left(\frac{r_{i}r_{jm}}{r_{i} + r_{jm}} + S\right)$$

where: i and j are the components contained in the 2nd order cut set.

(c) third order cut set

$$\lambda_{ML} = A + B + C + D + E + F$$

where:

$$A = \lambda_{im} \left[\lambda_j \lambda_k r_{im}^2 \, (A_1 + A_2) + \frac{r_{im}^2 S}{N} \, (A_3 + A_4) \right]$$

where:

$$A_1 = \frac{r_j}{(1+\lambda_j r_{im})(r_{im}+r_j)(1+\lambda_k r_{im} r_j/(r_{im}+r_j))}$$

$$A_2 = \frac{r_k}{(1+\lambda_k r_{im})(r_{im}+r_j)(1+\lambda_j r_{im} r_k/(r_{im}+r_k))}$$

$$A_3 = \frac{\lambda_{js} \lambda_k r_j}{(1+\lambda_{js} S)(r_{im}+r_j)(1+\lambda_k r_{im} r_j/(r_{im}+r_j))}$$

$$A_4 = \frac{\lambda_{ks} \lambda_j r_k}{(1+\lambda_{ks} S)(r_{im}+r_k)(1+\lambda_j r_{im} r_k/(r_{im}+r_k))}$$

$$A = \lambda_{im} \left[\lambda_j \lambda_k r_{im}^2 \left[\frac{r_j}{r_{im} + r_j} + \frac{r_k}{r_{im} + r_k} \right) + \frac{r_{im}^2 S}{N} \left(\frac{\lambda_{js} \lambda_k r_j}{r_{im} + r_j} + \frac{\lambda_j \lambda_{ks} r_k}{r_{im} + r_k} \right] \right]$$

and

$$B = \lambda_{im} \left[r_{im}^2 \frac{S}{N} (B_1 + B_2) + 2 \, \lambda_{js} \lambda_{ks} \frac{S^2}{N} (B_3) \right]$$

where:

$$B_1 = \frac{\lambda_j \lambda_{ks} r_j}{(1 + \lambda_j r_{im})(1 + \lambda_{ks} S)(r_{im} + r_j)}$$

$$B_2 = \frac{\lambda_k \lambda_{js} r_k}{(1 + \lambda_k r_{im})(1 + \lambda_{js} S)(r_{im} + r_k)}$$

$$B_3 = \frac{r_{im}}{(1 + \lambda_{js} S)(1 + \lambda_{ks} S)}$$

$$B = \lambda_{im} \left[\frac{r_{im}^2 S}{N} \left(\frac{\lambda_j \lambda_{ks} r_j}{r_{im} + r_j} + \frac{\lambda_k \lambda_{js} r_k}{r_{im} + r_k} \right) + 2\, \lambda_{js} \lambda_{ks} r_{im} \frac{S^2}{N} \right]$$

C and E are similar to A but for components j and k, respectively, i.e., i(jk) then j(ki) and k(ij).

D and F are similar to B but for components j and k, respectively, i.e., i(jk) then j(ki) and k(ij).

$$r_{ML} = \left(\frac{r_{im} R}{r_{im} + R} + \text{similar terms for components } j \text{ and } k. \right)$$

where:

$$R = \frac{A}{\lambda_{ML}} \frac{r_{im} r_j r_k}{r_{im} r_j + r_{im} r_k + r_j r_k} + \frac{B}{\lambda_{ML}} \left(\frac{r_{im} r_j r_k}{r_{im} r_j + r_{im} r_k + r_j r_k} + S \right)$$

where: i, j and k are the components contained in the 3rd order cut set.

3. PERMANENT AND TEMPORARY OUTAGES

3.1 Weather Independent

(a) first order cut set

$$\lambda_{TL} = \lambda_{it}$$

where: i is the component contained in the 1st order cut set.

(b) second order cut set

$$\lambda_{TL} = \lambda_i \lambda_{jt} \frac{r_i}{1 + \lambda_{jt} r_i} + \lambda_j \lambda_{it} \frac{r_j}{1 + \lambda_{it} r_j}$$

$$= \lambda_i \lambda_{jt} r_i + \lambda_j \lambda_{it} r_j$$

where: i and j are the components contained in the 2nd order cut set.

(c) third order cut set

$$\lambda_{TL} = A + B + C$$

where:

$$A = \frac{\lambda_i \lambda_j \lambda_{kt} r_i r_j}{1 + \lambda_i r_i + \lambda_j r_j + \lambda_i \lambda_j r_i r_j}$$

B and C are similar to A but for components j and k, respectively, i.e., i(jk) then j(ki) and k(ij).

$$\lambda_{TL} = \lambda_i \lambda_j \lambda_{kt} r_i r_j + \lambda_j \lambda_k \lambda_{it} r_j r_k + \lambda_k \lambda_i \lambda_{jt} r_k r_i$$

where: i, j and k are the components contained in the 3rd order cut set.

3.2 Weather Dependent

3.2.1 Repair Activites Continued in Adverse Weather

(a) first order cut set

$$\lambda_{TL} = \frac{N}{N + S} \lambda_{it} + \frac{S}{N + S} \lambda_{its}$$

where: i is the component contained in the 1st order cut set.

(b) second order cut set

$$
\begin{aligned}
\lambda_{TL} = \frac{N}{N+S} \Bigg(& \frac{\lambda_i \lambda_{jt} r_i}{1+\lambda_{jt} r_i} + \frac{\lambda_j \lambda_{it} r_j}{1+\lambda_{it} r_j} \\
& + \frac{S}{N} \Bigg[\frac{\lambda_i \lambda_{jts} r_i^2}{[1+\lambda_{jts} S r_i/(S+r_i)](S+r_i)} + \\
& \frac{\lambda_j \lambda_{its} r_j^2}{[1+\lambda_{its} S r_j/(S+r_j)](S+r_j)} \Bigg] \\
& + \frac{S}{N+S} \Bigg(\frac{\lambda_{is} \lambda_{jt} N r_i}{(N+r_i)[1+\lambda_{jt} N r_i/(N+r_i)]} + \\
& \frac{\lambda_{js} \lambda_{it} N r_j}{(N+r_j)[1+\lambda_{it} N r_j/(N+r_j)]} + \\
& \frac{\lambda_{is} \lambda_{jts} r_i S}{[1+\lambda_{jts} S r_i/(S+r_i)](S+r_i)} + \\
& \frac{\lambda_{js} \lambda_{its} r_j S}{[1+\lambda_{its} S r_j/(S+r_j)](S+r_j)} \Bigg)
\end{aligned}
$$

$$
\begin{aligned}
= \frac{N}{N+S} \Bigg[& \lambda_i \lambda_{jt} r_i + \lambda_j \lambda_{it} r_j + \frac{S}{N} \Bigg(\frac{\lambda_i \lambda_{jts} r_i^2}{S+r_i} + \\
& \frac{\lambda_j \lambda_{its} r_j^2}{S+r_j} \Bigg) \Bigg] \\
+ \frac{S}{N+S} \Bigg[& \frac{\lambda_{is} \lambda_{jt} N r_i}{N+r_i} + \frac{\lambda_{js} \lambda_{it} N r_j}{N+r_j} \\
& + \frac{\lambda_{is} \lambda_{jts} S r_i}{S+r_i} + \frac{\lambda_{js} \lambda_{its} S r_j}{S+r_j} \Bigg]
\end{aligned}
$$

where: i and j are the components contained in the 2nd order cut set.

(c) third order cut set

$$\lambda_{TL} = A + B$$

where:

$$A = \frac{N}{N+S}\left[\lambda_i\left(r_i^2\,(A_1 + A_2) + \frac{Sr_i^3}{S+r_i}\,(A_3 + A_4)\right) + \text{similar terms for components } j \text{ and } k\text{, i.e., } i(jk) \text{ then } j(ki) \text{ and } k(ij).\right]$$

$$+ \frac{S}{N+S}\left[\lambda_{is}\left(\frac{N^2r_i^2}{N+r_i}\,(A_5 + A_6) + \frac{NSr_i^2}{S+r_i}(A_7 + A_8)\right) + \text{similar terms for components } j \text{ and } k\text{, i.e., } i(jk) \text{ then } j(ki) \text{ and } k(ij).\right]$$

where:

$$A_1 = \frac{\lambda_j\lambda_{kt}r_j}{(1+\lambda_j r_i)(r_i+r_j)[1+\lambda_{kt}r_ir_j/(r_i+r_j)]}$$

$$A_2 = \frac{\lambda_k\lambda_{jt}r_k}{(1+\lambda_k r_i)(r_i+r_k)[1+\lambda_{jt}r_ir_k/(r_i+r_k)]}$$

$$A_3 = \frac{\lambda_{js}\lambda_{kt}r_j}{(1+\lambda_{js}r_i)(1+\lambda_{kt}Nr_ir_j/N_{ij})(N_{ij})}$$

$$A_4 = \frac{\lambda_{ks}\lambda_{jt}r_k}{(1+\lambda_{ks}r_i)(1+\lambda_{jt}Nr_ir_k/N_{ik})(N_{ik})}$$

$$A_5 = \frac{\lambda_j\lambda_{kt}r_j}{(1+\lambda_j r_i)(N_{ij})[1+\lambda_{kt}Nr_ir_j/N_{ij}]}$$

$$A_6 = \frac{\lambda_k\lambda_{jt}r_k}{(1+\lambda_k r_i)(N_{ik})[1+\lambda_{jt}Nr_ir_k/N_{ik}]}$$

$$A_7 = \frac{\lambda_{js}\lambda_{kt}r_j}{(1+\lambda_{js}r_i)(N_{ij})[1+\lambda_{kt}Nr_ir_j/N_{ij}]}$$

$$A_8 = \frac{\lambda_{ks}\lambda_{jt}r_k}{(1+\lambda_{ks}r_i)(N_{ik})[1+\lambda_{jt}Nr_ir_k/N_{ik}]}$$

$$\begin{aligned}
A = \frac{N}{N+S}\Bigg[\lambda_i\Bigg(r_i^{\,2}\left(\frac{\lambda_j\lambda_{kt}r_j}{r_i+r_j}+\frac{\lambda_k\lambda_{jt}r_k}{r_i+r_k}\right) \\
+\frac{Sr_i^{\,3}}{S+r_i}\left(\frac{\lambda_{js}\lambda_{kt}r_j}{Nr_i+Nr_j+r_ir_j}+\right. \\
\left.\frac{\lambda_{ks}\lambda_{jt}r_k}{Nr_i+Nr_k+r_ir_k}\right)\Bigg) \\
+\text{ similar terms for components j and k,} \\
\text{i.e., i(jk) then j(ki) and k(ij).}\Bigg]
\end{aligned}$$

$$\begin{aligned}
+\frac{S}{N+S}\Bigg[\lambda_{is}\Bigg(\frac{N^2r_i^{\,2}}{N+r_i}\left(\frac{\lambda_j\lambda_{kt}r_j}{Nr_i+Nr_j+r_ir_j}+\right. \\
\left.\frac{\lambda_k\lambda_{jt}r_k}{Nr_i+Nr_k+r_ir_k}\right) \\
+\frac{NSr_i^{\,2}}{S+r_i}\left(\frac{\lambda_{js}\lambda_{kt}r_j}{Nr_i+Nr_j+r_ir_j}+\right. \\
\left.\frac{\lambda_{ks}\lambda_{jt}r_k}{Nr_i+Nr_k+r_ir_k}\right)\Bigg) \\
+\text{ similar terms for components j and k,} \\
\text{i.e., i(jk) then j(ki) and k(ij).}\Bigg]
\end{aligned}$$

and

$$\begin{aligned}
B = \frac{N}{N+S}\Bigg[\lambda_i\Bigg(\frac{S^2r_i^{\,3}}{(S+r_i)N}(B_1+B_2)+ \\
\frac{r_i^{\,3}}{N}(B_3+B_4)\Bigg)+ \\
\text{similar terms for components j and k,} \\
\text{i.e., i(jk) then j(ki) and k(ij).}\Bigg]
\end{aligned}$$

$$+\frac{S}{N+S}\left[\lambda_{is}\left(\frac{S^2 r_i^{\,2}}{(S+r_i)}\;(B_5+B_6)\;+\;\frac{r_i^{\,3}NS}{N+r_i}\;(B_7+B_8)\right)+\right.$$

$$\left.\text{similar terms for components } j \text{ and } k\text{, i.e., } i(jk) \text{ then } j(ki) \text{ and } k(ij).\right]$$

where:

$$B_1 = \frac{\lambda_{js}\lambda_{kts}r_j}{(S_{ij})[1+\lambda_{js}Sr_i/(S+r_i)][1+\lambda_{kts}Sr_ir_j/S_{ij}]}$$

$$B_2 = \frac{\lambda_{ks}\lambda_{jts}r_k}{(S_{ik})[1+\lambda_{ks}Sr_i/(S+r_i)][1+\lambda_{jts}Sr_ir_k/S_{ik}]}$$

$$B_3 = \frac{\lambda_j\lambda_{kts}r_j^{\,2}}{(r_i+r_j)(1+\lambda_jr_i)[1+\lambda_{kts}Sr_ir_j/S_{ij}](S_{ij})}$$

$$B_4 = \frac{\lambda_k\lambda_{jts}r_k^{\,2}}{(r_i+r_k)(1+\lambda_kr_i)[1+\lambda_{jts}Sr_ir_k/S_{ik}](S_{ik})}$$

$$B_5 = \frac{\lambda_{js}\lambda_{kts}r_j}{[1+\lambda_{js}Sr_i/(S+r_i)](S_{ij})[1+\lambda_{kts}Sr_ir_j/S_{ij}]}$$

$$B_6 = \frac{\lambda_{ks}\lambda_{jts}r_k}{[1+\lambda_{ks}Sr_i/(S+r_i)](S_{ik})[1+\lambda_{jts}Sr_ir_k/S_{ik}]}$$

$$B_7 = \frac{\lambda_j\lambda_{kts}r_j^{\,2}}{[1+\lambda_jNr_i/(N+r_i)](N_{ij}S_{ij})[1+\lambda_{kts}Sr_ir_j/S_{ij}]}$$

$$B_8 = \frac{\lambda_k\lambda_{jts}r_k^{\,2}}{[1+\lambda_kNr_i/(N+r_i)](N_{ik}S_{ik})[1+\lambda_{jts}Sr_ir_k/S_{ik}]}$$

where:

$$N_{ij} = Nr_i + Nr_j + r_ir_j$$

$$N_{ik} = Nr_i + Nr_k + r_ir_k$$

$$S_{ij} = Sr_i + Sr_j + r_i r_j$$

$$S_{ik} = Sr_i + Sr_k + r_i r_k$$

$$\begin{aligned}
B = \frac{N}{N + S} \Bigg[\lambda_i \Bigg(& \frac{S^2 r_i^3}{N(S+r_i)} \left(\frac{\lambda_{js}\lambda_{kts} r_j}{Sr_i+Sr_j+r_i r_j} + \frac{\lambda_{ks}\lambda_{jts} r_k}{Sr_i+Sr_k+r_i r_k} \right) \\
& + \frac{r_i^3 S}{N} \left(\frac{\lambda_j \lambda_{kts} r_j^2}{(r_i+r_j)(Sr_i+Sr_j+r_i r_j)} + \frac{\lambda_k \lambda_{jts} r_k^2}{(r_i+r_k)(Sr_i+Sr_k+r_i r_k)} \right) \Bigg) \\
& + \text{similar terms for components j and k, i.e., i(jk) then j(ki) and k(ij).} \Bigg] \\
+ \frac{S}{N + S} \Bigg[\lambda_{is} \Bigg(& \frac{S^2 r_i^2}{S + r_i} \left(\frac{\lambda_{js}\lambda_{kts} r_j}{Sr_i+Sr_j+r_i r_j} + \frac{\lambda_{ks}\lambda_{jts} r_k}{Sr_i+Sr_k+r_i r_k} \right) \\
& + \frac{r_i^3 NS}{N + r_i} \left(\frac{\lambda_{js}\lambda_{kts} r_j^2}{(Sr_i+Sr_j+r_i r_j)(Nr_i+Nr_j+r_i r_j)} + \frac{\lambda_{ks}\lambda_{jts} r_k^2}{(Sr_i+Sr_k+r_i r_k)(Nr_i+Nr_k+r_i r_k)} \right) \Bigg) \\
& + \text{similar terms for components j and k, i.e., i(jk) then j(ki) and k(ij).} \Bigg]
\end{aligned}$$

where: i, j and k are the components contained in the 3rd order cut set.

3.2.2 Repair Activities Discontinued in Adverse Weather

(a) first order cut set

$$\lambda_{TL} = \frac{N}{N+S}\lambda_{it} + \frac{S}{N+S}\lambda_{its}$$

where: i is the component contained in the 1st order cut set.

(b) second order cut set

$$\lambda_{TL} = A + B$$

where:

$$A = \frac{N}{N+S}\left(\frac{\lambda_i \lambda_{jt} r_i}{1 + \lambda_{jt} r_i} + \frac{\lambda_j \lambda_{it} r_j}{1 + \lambda_{it} r_j} + \right.$$

$$\left. \frac{S}{N}\left(\frac{\lambda_i \lambda_{jts} r_i}{1 + \lambda_{jts} S} + \frac{\lambda_j \lambda_{its} r_j}{1 + \lambda_{its} S} \right) \right]$$

and

$$B = \frac{S}{N+S}\left(\frac{\lambda_{is} \lambda_{jts} S}{1 + \lambda_{jts} S} + \frac{\lambda_{js} \lambda_{its} S}{1 + \lambda_{its} S} + \right.$$

$$\left. \frac{\lambda_{is} \lambda_{jt} r_i}{1 + \lambda_{jt} r_i} + \frac{\lambda_{js} \lambda_{it} r_j}{1 + \lambda_{it} r_j} \right)$$

$$\lambda_{TL} = \frac{N}{N+S}\left[\lambda_i \lambda_{jt} r_i + \lambda_j \lambda_{it} r_j + \frac{S}{N}\left(\lambda_i \lambda_{jts} r_i + \lambda_j \lambda_{its} r_j \right) \right]$$

$$+ \frac{S}{N+S}\left[\lambda_{is} \lambda_{jt} r_i + \lambda_{js} \lambda_{it} r_j + \lambda_{is} \lambda_{jts} S + \lambda_{its} \lambda_{js} S \right]$$

where: i and j are the components contained in the 2nd order cut set.

(c) third order cut set

$$\lambda_{TL} = A + B$$

where:

$$A = \frac{N}{N + S} \left[\lambda_i r_i^2 \left((A_1 + A_2) + \frac{S}{N} (A_3 + A_4) \right] + \right.$$

$$\left. \begin{array}{l} \text{similar terms for components j and k,} \\ \text{i.e., i(jk) then j(ki) and k(ij).} \end{array} \right]$$

$$+ \frac{S}{N + S} \left[\lambda_{is} \left(r_i^2 (A_1 + A_2) + S r_i (A_3 + A_4) \right] + \right.$$

$$\left. \begin{array}{l} \text{similar terms for components j and k,} \\ \text{i.e., i(jk) then j(ki) and k(ij).} \end{array} \right]$$

where:

$$A_1 = \frac{\lambda_j \lambda_{kt} r_j}{(r_i + r_j)(1 + \lambda_j r_i)[1 + \lambda_{kt} r_i r_j / (r_i + r_j)]}$$

$$A_2 = \frac{\lambda_k \lambda_{jt} r_k}{(r_i + r_k)(1 + \lambda_k r_i)[1 + \lambda_{jt} r_i r_k / (r_i + r_k)]}$$

$$A_3 = \frac{\lambda_{js} \lambda_{kt} r_j}{(r_i + r_j)(1 + \lambda_{js} S)[1 + \lambda_{kt} r_i r_j / (r_i + r_j)]}$$

$$A_4 = \frac{\lambda_{ks} \lambda_{jt} r_k}{(r_i + r_k)(1 + \lambda_{ks} S)[1 + \lambda_{jt} r_i r_k / (r_i + r_k)]}$$

$$A \approx \frac{N}{N + S} \left[\lambda_i \left(r_i^2 \left(\frac{\lambda_j \lambda_{kt} r_j}{r_i + r_j} + \frac{\lambda_k \lambda_{jt} r_k}{r_i + r_k} \right) + \frac{S}{N} \left(\frac{\lambda_{js} \lambda_{kt} r_j}{r_i + r_j} + \frac{\lambda_{ks} \lambda_{jt} r_k}{r_i + r_k} \right) \right) \right.$$

$$\left. + \begin{array}{l} \text{similar terms for components j and k,} \\ \text{i.e., i(jk) then j(ki) and k(ij).} \end{array} \right]$$

$$+ \frac{S}{N+S}\Bigg[\ \lambda_{is}\Bigg(r_i^{\,2}\left(\frac{\lambda_j \lambda_{kt} r_j}{r_i + r_j} + \frac{\lambda_k \lambda_{jt} r_k}{r_i + r_k}\right)$$

$$+ S r_i \left(\frac{\lambda_{js} \lambda_{kt} r_j}{r_i + r_j} + \frac{\lambda_{jt} \lambda_{ks} r_k}{r_i + r_k}\right)\Bigg)$$

$$+ \text{ similar terms for components j and k, i.e., i(jk) then j(ki) and k(ij).}\Bigg]$$

and

$$B = \frac{N}{N+S}\Bigg[\lambda_i \Bigg(\frac{Sr_i^{\,2}}{N} (B_1 + B_2) +$$

$$\frac{S^2 r_i}{N} (B_3 + B_4)\Bigg) +$$

$$\text{similar terms for components j and k, i.e., i(jk) then j(ki) and k(ij).}\Bigg]$$

$$+ \frac{S}{N+S}\Bigg[\lambda_{is} \Bigg(\frac{Sr_i^{\,2}}{N} (B_1 + B_2) +$$

$$S^2 (B_3 + B_4)\Bigg) +$$

$$\text{similar terms for components j and k, i.e., i(jk) then j(ki) and k(ij).}\Bigg]$$

where:

$$B_1 = \frac{\lambda_j \lambda_{kts} r_j}{(r_i + r_j)(1+ \lambda_j r_i)[1+ \lambda_{kts} S]}$$

$$B_2 = \frac{\lambda_k \lambda_{jts} r_k}{(r_i + r_k)(1+ \lambda_k r_i)[1+ \lambda_{jts} S]}$$

$$B_3 = \frac{\lambda_{js} \lambda_{kts}}{(1+ \lambda_{js} S)(1+ \lambda_{kts} S)}$$

$$B_4 = \frac{\lambda_{ks} \lambda_{jts}}{(1+ \lambda_{ks} S)(1+ \lambda_{jts} S)}$$

$$
\begin{aligned}
B \simeq \frac{N}{N+S} \Bigg[\lambda_i & \left(\frac{S}{N}^2 r_i \left(\lambda_{jts}\lambda_{ks} + \lambda_{kts}\lambda_{js} \right) \right. \\
& \left. + \frac{S}{N} r_i^{\,2} \left(\frac{\lambda_j \lambda_{kts} r_j}{r_i + r_j} + \frac{\lambda_k \lambda_{jts} r_k}{r_i + r_k} \right) \right) \\
& + \text{similar tems for components j and k,} \\
& \quad \text{i.e., i(jk) then j(ki) and k(ij).} \Bigg] \\
+ \frac{S}{N+S} \Bigg[\lambda_{is} & \left(\lambda_{jts}\lambda_{ks}S + \lambda_{kts}\lambda_{js}S \right. \\
& \left. + \frac{S}{N} r_i^{\,2} \left(\frac{\lambda_j \lambda_{kts} r_j}{r_i + r_j} + \frac{\lambda_{jts} \lambda_k r_k}{r_i + r_k} \right) \right) \\
& + \text{similar terms for components j and k,} \\
& \quad \text{i.e., i(jk) then j(ki) and k(ij)} \Bigg]
\end{aligned}
$$

where: i, j and k are the components contained in the 3rd order cut set.

4. PERMANENT, MAINTENANCE AND TEMPORARY OUTAGES

4.1 Weather Independent

(a) first order cut set

$$\lambda_{MT} = \lambda_{im}$$

where: i is the component contained in the 1st order cut set.

(b) second order cut set

$$\lambda_{MT} = \lambda_{im} \frac{\lambda_{jt} r_{im}}{(1 + \lambda_{jt} r_{im})} + \lambda_{jm} \frac{\lambda_{it} r_{jm}}{(1 + \lambda_{it} r_{jm})}$$

$$\simeq \lambda_{im}\lambda_{jt}r_{im} + \lambda_{jm}\lambda_{it}r_{jm}$$

where: i and j are the components contained in the 2nd order cut set.

(c) third order cut set

$$\lambda_{MT} = A + B + C$$

where:

$$A = \lambda_{im}\left[\lambda_j\lambda_{kt}\frac{r_{im}^2 r_j}{(1+\lambda_j r_{im})(r_{im}+r_j)(1+\lambda_{kt} r_{im} r_j/(r_{im}+r_j))}\right.$$
$$\left.+\lambda_k\lambda_{jt}\frac{r_{im}^2 r_k}{(1+\lambda_k r_{im})(r_{im}+r_k)(1+\lambda_{jt} r_{im} r_k/(r_{im}+r_k))}\right]$$
$$\simeq \lambda_{im}\left[\lambda_j\lambda_{kt}\frac{r_{im}^2 r_j}{r_{im}+r_j} + \lambda_{jt}\lambda_k\frac{r_{im}^2 r_k}{r_{im}+r_k}\right]$$

B and C are similar to A but for components j and k respectively, i.e., i(jk) then j(ki) and k(ij).

where: i, j and k are the components contained in the 3rd order cut set.

4.2 Weather Dependent

4.2.1 Repair and Maintenance Activities Continued in Adverse Weather

(a) first order cut set

$$\lambda_{MT} = \frac{N}{N+S}\lambda_{it} + \frac{S}{N+S}\lambda_{its}$$

where: i is the component contained in the 1st order cut set.

(b) second order cut set

$$\lambda_{MT} = \lambda_{im}\left(\lambda_{jt}\frac{r_{im}}{1+\lambda_{jt}r_{im}} + \lambda_{jts}\frac{Sr_{im}^2}{N(S+r_{im})(1+\lambda_{jts}Sr_{im}/(S+r_{im}))}\right]$$
$$+\lambda_{jm}\left(\lambda_{it}\frac{r_{jm}}{1+\lambda_{it}r_{jm}} + \lambda_{its}\frac{Sr_{jm}^2}{N(S+r_{jm})(1+\lambda_{its}Sr_{jm}/(S+r_{jm}))}\right]$$
$$= \lambda_{im}\left[\lambda_{jt}r_{im} + \lambda_{jts}\frac{Sr_{im}^2}{N(S+r_{im})}\right] + \lambda_{jm}\left[\lambda_{it}r_{jm} + \lambda_{its}\frac{Sr_{jm}^2}{N(S+r_{jm})}\right]$$

where: i and j are the components contained in the 2nd order cut set.

(c) third order cut set

$$\lambda_{MT} = A + B + C$$

where:

$$A = \lambda_{im} \left[r_{im}^2 (A_1 + A_2) + \frac{S}{N} r_{im}^3 (A_3 + A_4) + \frac{S r_{im}^3}{S + r_{im}} (A_5 + A_6) + \frac{S^2 r_{im}^3}{N(S + r_{im})} (A_7 + A_8) \right]$$

where:

$$A_1 = \frac{\lambda_j \lambda_{kt} r_j}{(r_{im} + r_j)(1 + \lambda_j r_{im})[1 + \lambda_{kt} r_{im} r_j/(r_{im} + r_j)]}$$

$$A_2 = \frac{\lambda_k \lambda_{jt} r_k}{(r_{im} + r_k)(1 + \lambda_k r_{im})[1 + \lambda_{jt} r_{im} r_k/(r_{im} + r_j)]}$$

$$A_3 = \frac{\lambda_j \lambda_{kts} r_j^2}{(r_{im} + r_j)(1 + \lambda_j r_{im})(S_{ij})(1 + \lambda_{kts} r_{im} r_j S/S_{ij})}$$

$$A_4 = \frac{\lambda_k \lambda_{jts} r_k^2}{(r_{im} + r_k)(1 + \lambda_k r_{im})(S_{ik})(1 + \lambda_{jts} r_{im} r_k S/S_{ik})}$$

$$A_5 = \frac{\lambda_{js} \lambda_{kt} r_j}{(S + r_{im})[1 + \lambda_{js} S r_{im}/(S + r_{im})](N_{ij})(1 + \lambda_{kt} r_{im} r_j N/N_{ij})}$$

$$A_6 = \frac{\lambda_{ks} \lambda_{jt} r_k}{(S + r_{im})[1 + \lambda_{ks} S r_{im}/(S + r_{im})](N_{ik})(1 + \lambda_{jt} r_{im} r_k N/N_{ik})}$$

$$A_7 = \frac{\lambda_{js} \lambda_{kts} r_j}{[1 + \lambda_{js} S r_{im}/(S + r_{im})](S_{ij})(1 + \lambda_{kts} S r_{im} r_j/S_{ij})}$$

$$A_8 = \frac{\lambda_{ks} \lambda_{jts} r_k}{[1 + \lambda_{ks} S r_{im}/(S + r_{im})](S_{ik})(1 + \lambda_{jts} S r_{im} r_k/S_{ik})}$$

$$A = \lambda_{im} \left[\frac{\lambda_j \lambda_{kt} r_{im}^2 r_j}{r_{im} + r_j} + \frac{\lambda_k \lambda_{jt} r_{im}^2 r_k}{r_{im} + r_k} \right.$$

$$+ \frac{S}{N} r_{im}^3 \left(\frac{\lambda_j \lambda_{kts} r_j^2}{(r_{im}+r_j)(Sr_{im}+Sr_j+r_{im}r_j)} \right.$$

$$\left. \frac{\lambda_k \lambda_{jts} r_k^2}{(r_{im}+r_k)Sr_{im}+Sr_k+r_{im}r_k)} \right)$$

$$+ \frac{Sr_{im}^3}{S + r_{im}} \left(\frac{\lambda_{js} \lambda_{kt} r_j}{Nr_{im}+Nr_j+r_{im}r_j} + \frac{\lambda_{ks} \lambda_{jt} r_k}{Nr_{im}+Nr_k+r_{im}r_k} \right)$$

$$\left. + \frac{S^2 r_{im}^3}{N(S+r_{im})} \left(\frac{\lambda_{js} \lambda_{kts} r_j}{Sr_{im}+Sr_j+r_{im}r_j} + \frac{\lambda_{ks} \lambda_{jts} r_k}{Sr_{im}+Sr_k+r_{im}r_k} \right) \right]$$

B and C are similar to A but for components j and k respectively, i.e., i(jk) then j(ki) and k(ij).

and

$$N_{ij} = Nr_{im} + Nr_j + r_{im}r_j$$

$$N_{ik} = Nr_{im} + Nr_k + r_{im}r_k$$

$$S_{ij} = Sr_{im} + Sr_j + r_{im}r_j$$

$$S_{ik} = Sr_{im} + Sr_k + r_{im}r_k$$

where: i, j and k are the components contained in the 3rd order cut set.

4.2.2 Repair and Maintenance Activities Discontinued in Adverse Weather

(a) first order cut set

$$\lambda_{MT} = \frac{N}{N + S} \lambda_{it} + \frac{S}{N + S} \lambda_{its}$$

where: i is the component contained in the 1st order cut set.

(b) second order cut set

$$\lambda_{MT} = \lambda_{im}\left(\lambda_{jt}\frac{r_{im}}{1+\lambda_{jt}r_{im}} + \lambda_{jts}\frac{Sr_{im}}{(1+\lambda_{jts}S)N}\right)$$

$$+ \lambda_{jm}\left(\lambda_{it}\frac{r_{jm}}{1+\lambda_{it}r_{jm}} + \lambda_{its}\frac{Sr_{jm}}{(1+\lambda_{its}S)N}\right)$$

$$= \lambda_{im}\left[\lambda_{jt}r_{im} + \lambda_{jts}\frac{Sr_{im}}{N}\right] + \lambda_{jm}\left[\lambda_{it}r_{jm} + \lambda_{its}\frac{Sr_{jm}}{N}\right]$$

where: i and j are the components contained in the 2nd order cut set.

(c) third order cut set

$$\lambda_{MT} = A + B + C + D + E + F$$

where:

$$A = \lambda_{im}\left(r_{im}^{2}(A_1 + A_2) + \frac{r_{im}^{2}S}{N}(A_3 + A_4)\right)$$

where:

$$A_1 = \frac{\lambda_j\lambda_{kt}r_j}{(1+\lambda_j r_{im})(r_{im}+r_j)[1+\lambda_{kt}r_{im}r_j/(r_{im}+r_j)]}$$

$$A_2 = \frac{\lambda_k\lambda_{jt}r_k}{(1+\lambda_k r_{im})(r_{im}+r_k)[1+\lambda_{jt}r_{im}r_k/(r_{im}+r_k)]}$$

$$A_3 = \frac{\lambda_{js}\lambda_{kt}r_j}{(1+\lambda_{js}S)(r_{im}+r_j)[1+\lambda_{kt}r_{im}r_j/(r_{im}+r_j)]}$$

$$A_4 = \frac{\lambda_{ks}\lambda_{jt}r_k}{(1+\lambda_{ks}S)(r_{im}+r_k)[1+\lambda_{jt}r_{im}r_k/(r_{im}+r_j)]}$$

$$A = \lambda_{im}\left[r_{im}^{2}\left(\frac{\lambda_j\lambda_{kt}r_j}{r_{im}+r_j} + \frac{\lambda_k\lambda_{jt}r_k}{r_{im}+r_k}\right)\right.$$

$$\left. + \frac{S}{N}\left(\frac{\lambda_{js}\lambda_{kt}r_j}{r_{im}+r_j} + \frac{\lambda_{ks}\lambda_{jt}r_k}{r_{im}+r_k}\right)\right]$$

and

$$B = \lambda_{im} \left(r_{im}^2 \frac{S}{N} (B_1 + B_2) + \frac{S^2 r_{im}}{N} (B_3 + B_4) \right)$$

where:

$$B_1 = \frac{\lambda_j \lambda_{kts} r_j}{(1 + \lambda_j r_{im})(1 + \lambda_{kts} S)(r_{im} + r_j)}$$

$$B_2 = \frac{\lambda_k \lambda_{jts} r_k}{(1 + \lambda_k r_{im})(1 + \lambda_{jts} S)(r_{im} + r_k)}$$

$$B_3 = \frac{\lambda_{js} \lambda_{kts}}{(1 + \lambda_{js} S)(1 + \lambda_{kts} S)}$$

$$B_4 = \frac{\lambda_{ks} \lambda_{jts}}{(1 + \lambda_{ks} S)(1 + \lambda_{jts} S)}$$

$$B \simeq \lambda_{im} \left[\frac{r_{im}^2 S}{N} \left(\frac{\lambda_j \lambda_{kts} r_j}{r_{im} + r_j} + \frac{\lambda_k \lambda_{jts} r_k}{r_{im} + r_k} \right) + \frac{S^2}{N} r_{im} \left[\lambda_{js} \lambda_{kts} + \lambda_{ks} \lambda_{jts} \right] \right]$$

C and E are similar to A but for components j and k respectively, i.e., i(jk) then j(ki) and k(ij).

D and F are similar to B but for components j and k respectively, i.e., i(jk) then j(ki) and k(ij).

where: i, j and k are the components contained in the 3rd order cut set.

APPENDIX E

Table E.1 Reliability indices for all load points of the IEEE 14 bus network configuration (Figure 2.7) - repair activities is continued in adverse weather

Load point	Availability	Consumer failure frequency (f/yr)	Consumer failure rate (f/yr)	Average duration of interruption (hrs/r)	Total annual downtime (hrs/yr)
2	0.9995604	0.268216	0.268334	14.3584	3.8529
3	0.9995881	0.239030	0.239129	15.0956	3.6098
4	0.9990756	0.500525	0.500988	16.1781	8.1051
6	0.9926402	0.861405	0.867792	74.8446	64.950
7	0.9990044	0.550390	0.550939	15.8455	8.7299
8	0.9990185	0.535979	0.536506	16.0412	8.6062
9	0.9990380	0.520974	0.521475	16.1747	8.4347
10	0.9989214	0.595991	0.596635	15.8532	9.4586
11	0.9988465	0.646834	0.647581	15.6213	10.116
12	0.9989034	0.608441	0.609109	15.7867	9.6159
13	0.9995875	0.239497	0.239596	15.0883	3.6151
14	0.9995278	0.280401	0.280533	14.7528	4.1386
OVERALL	0.9901122	2.688520	2.715369	32.2174	87.482

Table E.2 Reliability indices for all load points of the IEEE 14 bus network configuration (Figure 2.7) - repair activities is discontinued in adverse weather

Load point	Availability	Consumer failurecy frequency (f/yr)	Consumer failure rate (f/yr)	Average duration of interruption (hrs/r)	Total annual downtime (hrs/yr)
2	0.9984685	0.144209	0.144430	93.0298	13.436
3	0.9984694	0.144093	0.144314	93.0521	13.429
4	0.9978022	0.16137	0.169510	113.830	19.295
6	0.9740868	0.675699	0.693674	335.947	233.038
7	0.9977963	0.169701	0.170076	113.755	19.347
8	0.9977152	0.174828	0.175228	114.484	20.061
9	0.9976735	0.176967	0.177379	115.162	20.427
10	0.9975548	0.183403	0.183852	116.790	21.472
11	0.9977610	0.172808	0.173196	113.500	19.658
12	0.9976413	0.178845	0.179268	115.532	20.711
13	0.9984886	0.141948	0.142163	93.2734	13.260
14	0.9981447	0.160854	0.161153	101.037	16.282
OVERALL	0.9586601	0.144596	2.237077	168.861	377.754

APPENDIX F

The computer algorithm for finding the first, second, third, etc., order of cut set from a set of paths leading to a particular consumer success is discribed in this section. Consider the system shown in Figure A.1. The system configuration have four possible paths leading to the output component #3, they are:

(i) 1 - 2 - 3
(ii) 5 - 4 - 3
(iii) 1 - 2 - 6 - 4 - 3
(iv) 5 - 4 - 6 - 2 - 3 .

STEP 1

Form a 'P' by 'Q' table, where 'P' is the total number of paths leading to the desired load point, and 'Q' is the total number of components in the given network configuration. For the example above, 'P' is four and 'Q' is six, therefore, form a '4 X 6' table.

P	1	2	3	4	5	6
1						
2						
3						
4						

Q

STEP 2

Scan through each path and cross the corresponding location of the component number within the path, e.g., the components within path (i) is 1,2, and 3, thus in the first row of the table column 1, 2 and 3 are crossed. The process is repeated for all paths. Hence, for the example, the resulting table is as follows:

P	1	2	3	4	5	6
1	X	X	X			
2			X	X	X	
3	X	X	X	X		X
4		X	X	X	X	X

Q

STEP 3

Next, scan through each colume of the table to locate those column with all rows crossed-out. This gives the minimum first order cut set. In the table above, column 3 is the only column which has all rows crossed-out. This means the desire load point within the given system has one first order cut set and it contains component #3.

STEP 4

All the cross which forms the first order cut set is removed from the table as shown below.

P	1	2	3	4	5	6
1	X	X				
2				X	X	
3	X	X		X		X
4		X		X	X	X

Q

The second order cut set is found by scaning through two columns at a time to locate combinations of any 2 columns that would allows all rows to have crosses. In the table above, it can be seen that columns 1 and 2 does not satisfy this condition since both columns 1 and 2 does not contribute a cross in row #2, hence 1-2 is not a second order cut set. On the other hand, columns 1 and 4, columns 1 and 5, columns 2 and 4, columns 2 and 5 does form a second order cut set. This is to say that for the system in Figure A.1, there are four secong order cut set, they are:

1-4, 2-4, 1-5, 2-5.

STEP 5

Using the same table and method as in STEP 4, the consecutive orders of minimum cut set can be found. Note that the maximum order of cut is limited to the total number of paths to the desired load point. Note also that the higher order of cut set cannot contain a lower order of cut set, e.g., if a second order cut set is 1-4, then a 1-4-5 or 1-4-6 cannot be considered as a third order minimum cut set.

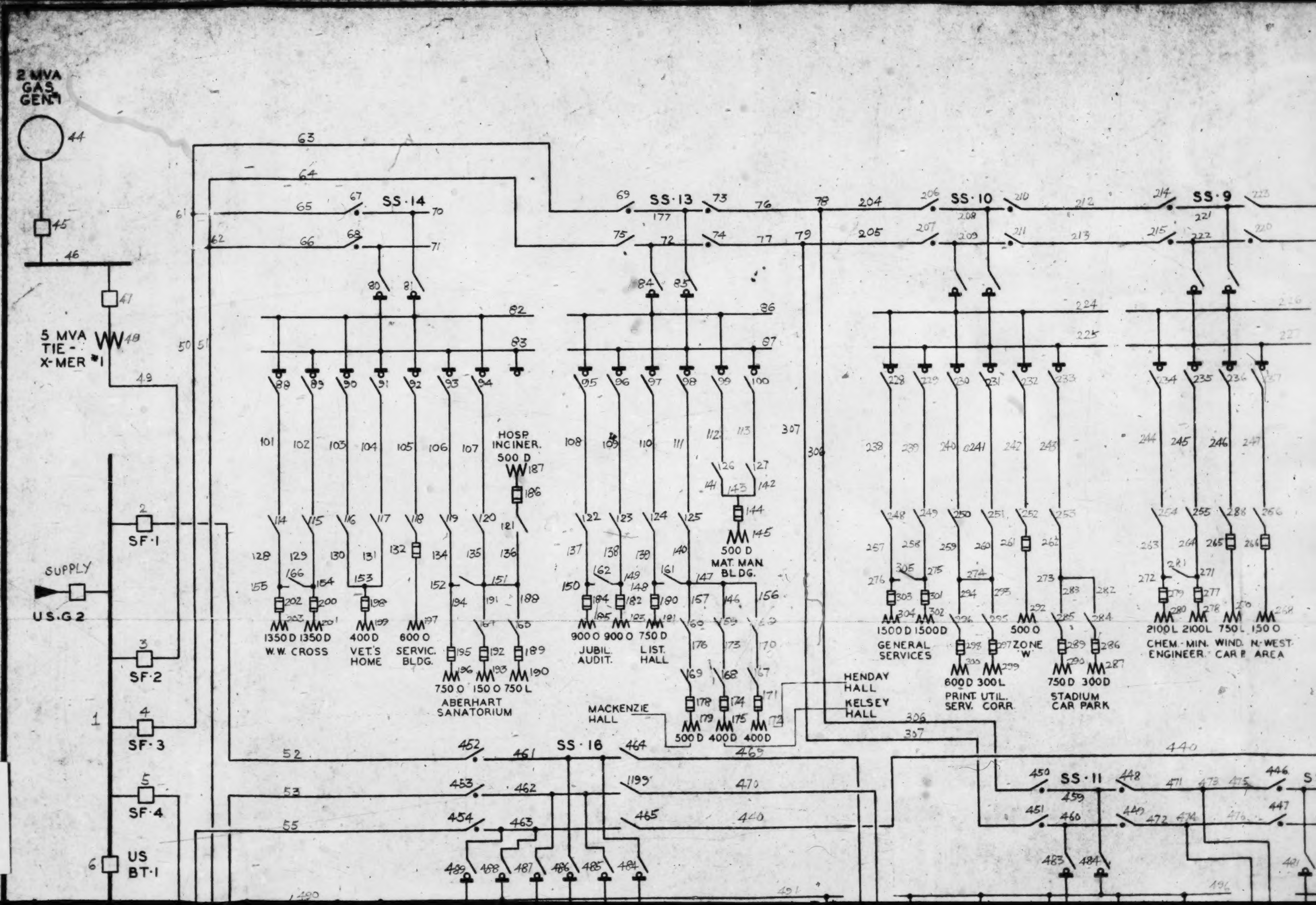
For the example aboves, the minimum cut sets are:

order of cut set	component(s) within cut set
1	3
2	1 , 4 1 , 5 2 , 4 2 , 5

There are no third or higher order cut set.

1

OF/DE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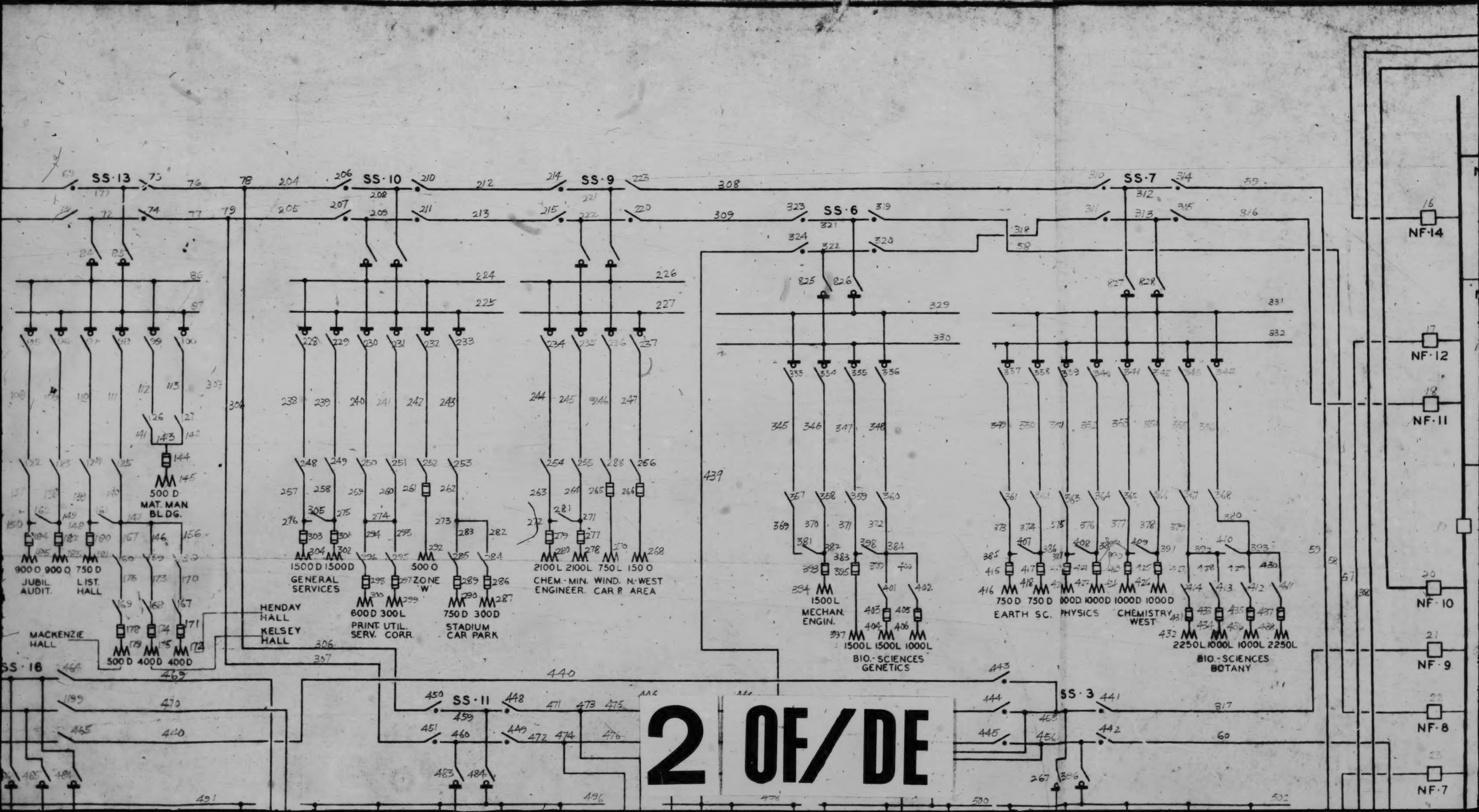
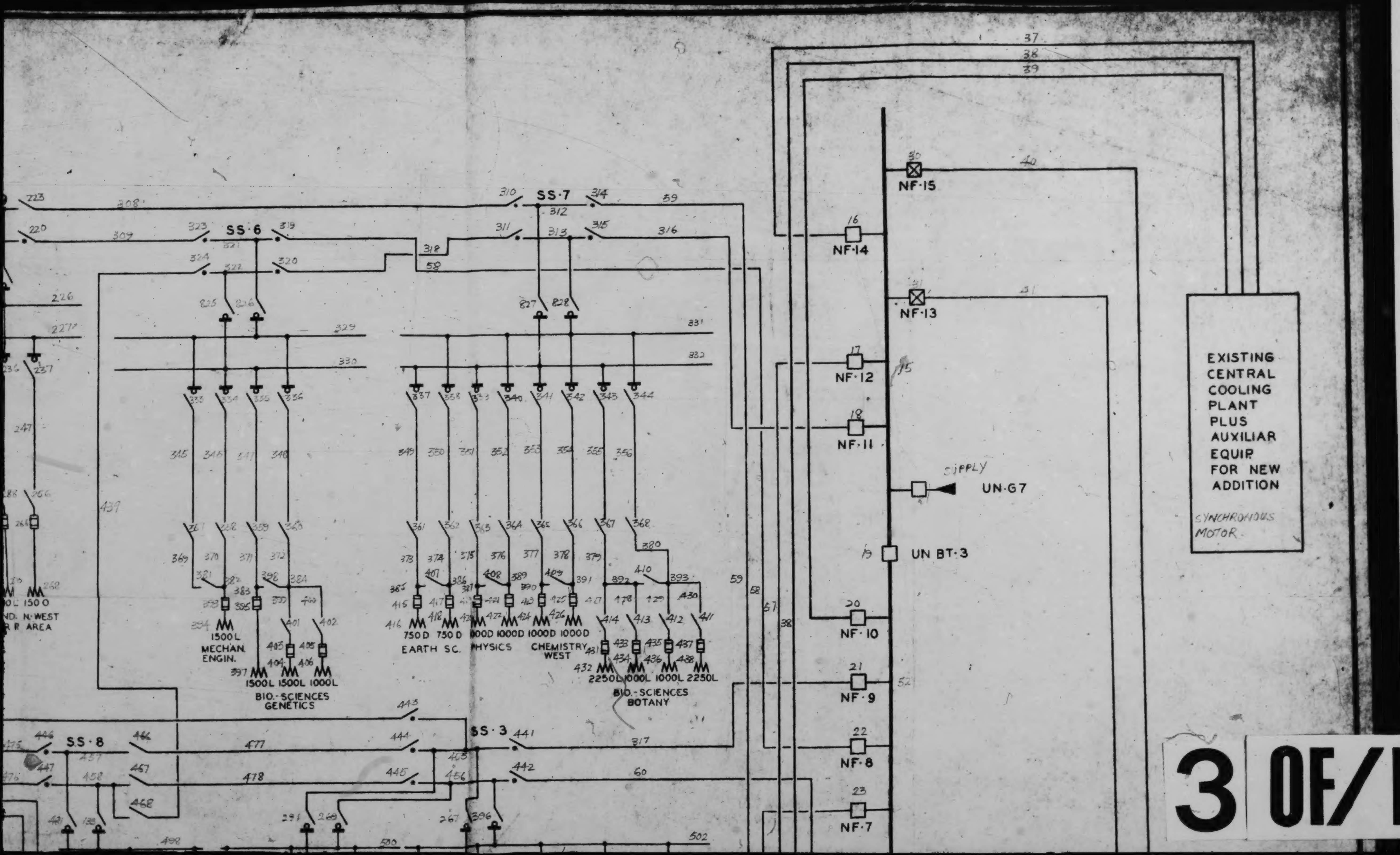
5 MVA TIE-X-MER #1
SUPPLY
US·G2
SF·1
SF·2
SF·3
SF·4
US BT·1
SS·14
SS·13
SS·10
SS·9
SS·16
SS·11
HOSP. INCINER. 500 D
1350 D 1350 D W.W. CROSS
400 D VET.'S HOME
600 O SERVIC. BLDG.
750 O 150 O 750 L ABERHART SANATORIUM
900 O 900 O JUBIL. AUDIT.
750 D LIST. HALL
500 D MAT. MAN. BLDG.
MACKENZIE HALL
HENDAY HALL
KELSEY HALL
500 D 400 D 400 D
1500 D 1500 D GENERAL SERVICES
600 D 300 L PRINT. SERV. UTIL. CORR.
500 O ZONE 'W'
750 D 300 D STADIUM CAR PARK
2100 L 2100 L CHEM.-MIN. ENGINEER.
750 L WIND. CAR P.
150 O N.-WEST AREA


SS·13
SS·10
SS·9
SS·7
SS·6
SS·16
SS·11
SS·3
500 D
MAT. MAN. BLDG.
900 D
JUBIL. AUDIT.
900 D
750 D
LIST. HALL
500 D
400 D
400 D
MACKENZIE HALL
HENDAY HALL
KELSEY HALL
1500 D
1500 D
GENERAL SERVICES
600 D
300 L
PRINT. SERV.
UTIL. CORR.
500 D
ZONE 'W'
750 D
300 D
STADIUM CAR PARK
2100 L
2100 L
CHEM.-MIN. ENGINEER.
750 L
WIND. CAR P.
150 D
N.-WEST AREA
1500 L
MECHAN. ENGIN.
1500 L
1500 L
1000 L
BIO.-SCIENCES GENETICS
750 D
750 D
EARTH SC.
1000 D
1000 D
PHYSICS
1000 D
1000 D
CHEMISTRY WEST
2250 L
1000 L
1000 L
2250 L
BIO.-SCIENCES BOTANY
NF·14
NF·12
NF·11
NF·10
NF·9
NF·8
NF·7

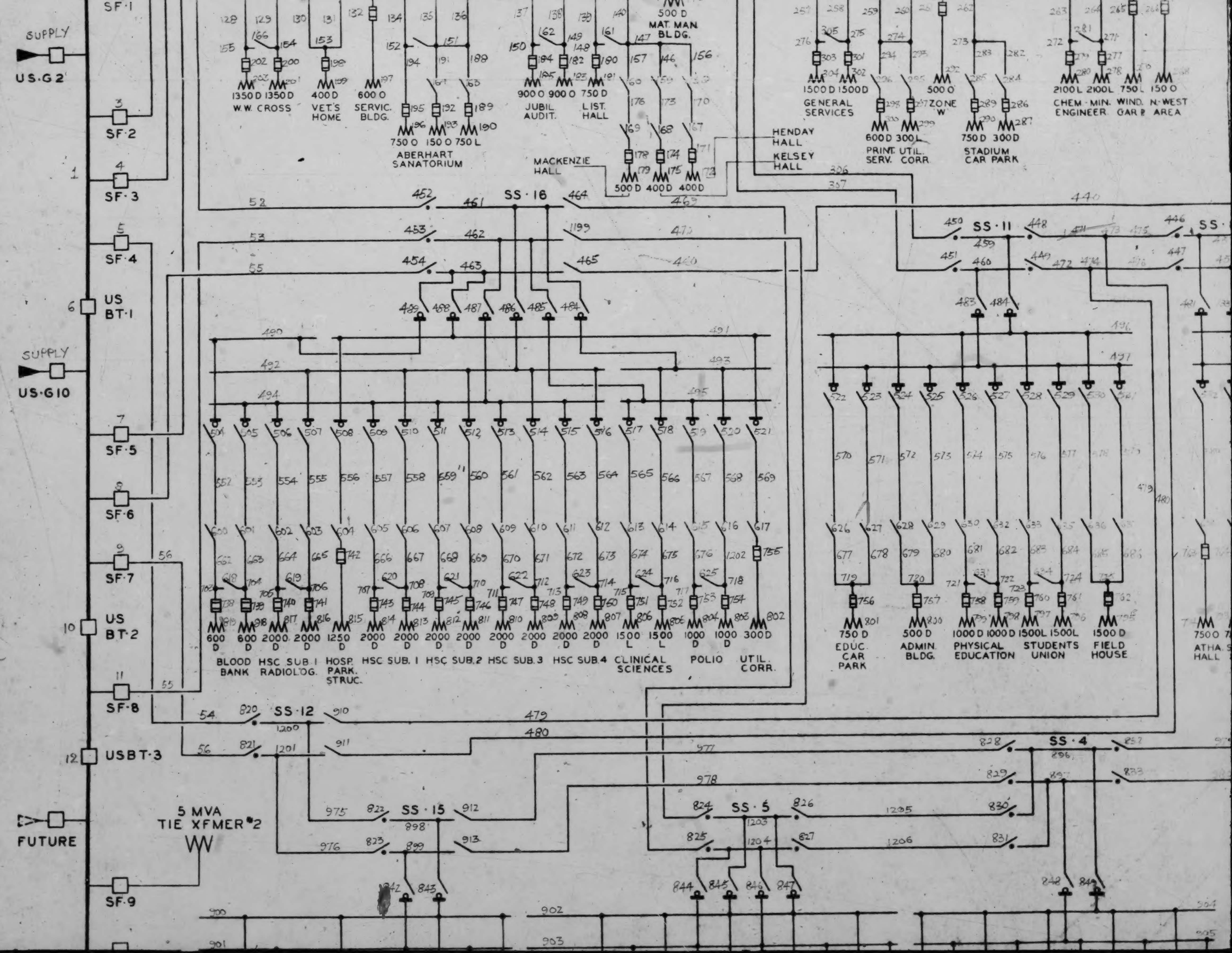
2 OF/DE

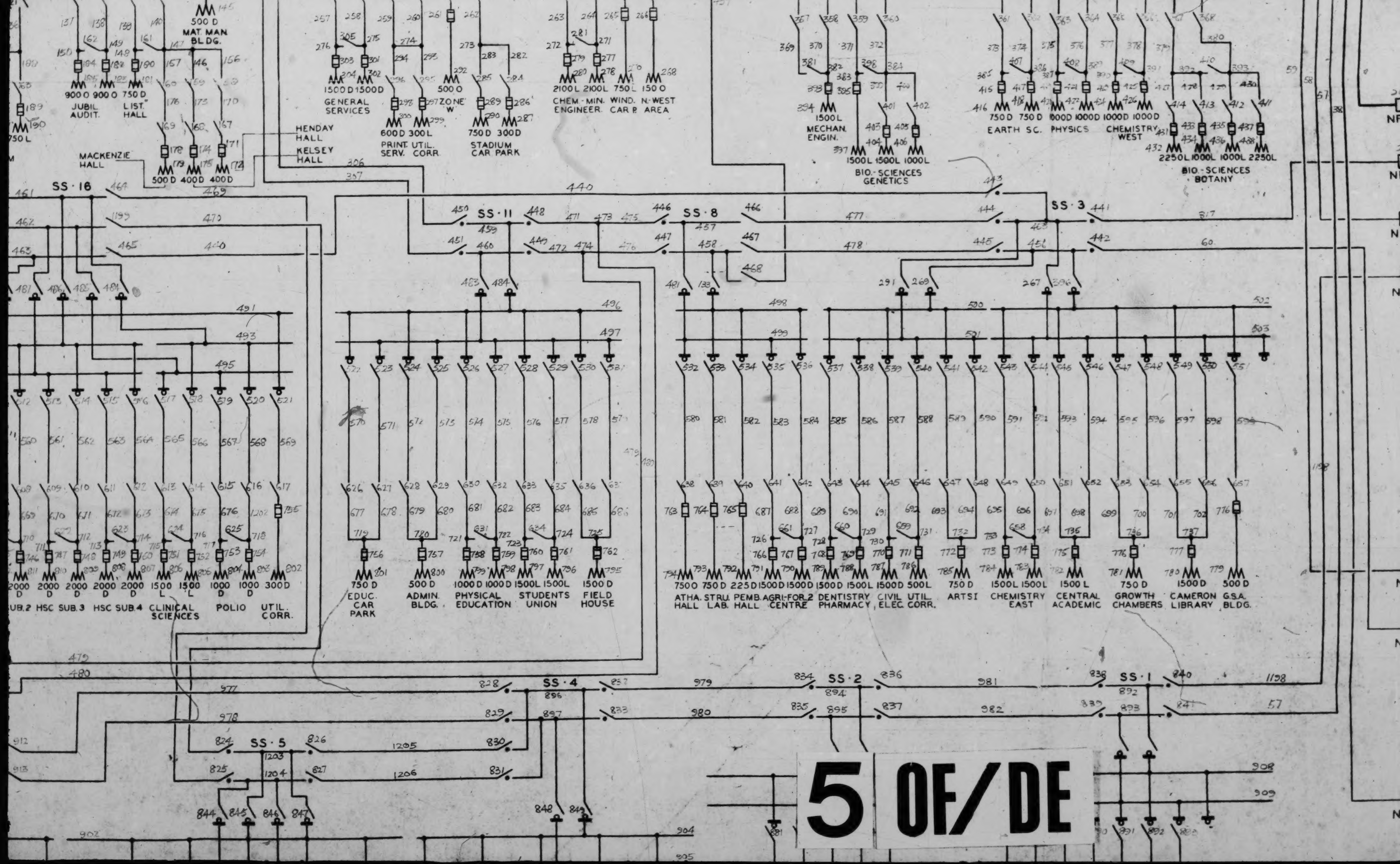

SS·7
SS·6
SS·8
SS·3
NF·15
NF·14
NF·13
NF·12
NF·11
NF·10
NF·9
NF·8
NF·7
SUPPLY
UN·G7
UN BT·3
EXISTING CENTRAL COOLING PLANT PLUS AUXILIAR EQUIP. FOR NEW ADDITION
SYNCHRONOUS MOTOR
1500L
MECHAN. ENGIN.
1500L 1500L 1000L
BIO.-SCIENCES GENETICS
750D 750D
EARTH SC.
1000D 1000D
PHYSICS
1000D 1000D
CHEMISTRY WEST
2250L 1000L 1000L 2250L
BIO.-SCIENCES BOTANY
1500
N-WEST
R AREA

3 OF/DE

4

OF/DE


SUPPLY
US·G2
SF·1
SF·2
SF·3
SF·4
US BT·1
SUPPLY
US·G10
SF·5
SF·6
SF·7
US BT·2
SF·8
USBT·3
FUTURE
SF·9
5 MVA TIE XFMER #2
1350 D 1350 D W.W. CROSS
400 D VET'S HOME
600 O SERVIC. BLDG.
750 O 150 O 750 L ABERHART SANATORIUM
900 O 900 O JUBIL AUDIT.
750 D LIST. HALL
500 D MAT. MAN. BLDG.
MACKENZIE HALL
500 D 400 D 400 D
HENDAY HALL
KELSEY HALL
1500 D 1500 D GENERAL SERVICES
600 D 300 L PRINT. SERV. UTIL. CORR
500 O ZONE 'W'
750 D 300 D STADIUM CAR PARK
2100 L 2100 L CHEM·MIN. ENGINEER
750 L WIND. GAR P.
150 O N·WEST AREA
SS·16
SS·11
SS·12
SS·15
SS·5
SS·4
600 D 600 D BLOOD BANK
2000 D HSC SUB 1 RADIOLOG.
2000 D
1250 D HOSP. PARK. STRUC.
2000 D 2000 D HSC SUB. 1
2000 D 2000 D HSC SUB. 2
2000 D 2000 D HSC SUB. 3
2000 D 2000 D HSC SUB. 4
1500 L 1500 L CLINICAL SCIENCES
1000 D 1000 D POLIO
300 D UTIL. CORR.
750 D EDUC. CAR PARK
500 D ADMIN. BLDG.
1000 D 1000 D PHYSICAL EDUCATION
1500 L 1500 L STUDENTS UNION
1500 D FIELD HOUSE
750 O ATHA. HALL
52
53
55
54
56
440
479
480
977
978
1205
1206
900
901
902
903



500 D
MAT. MAN. BLDG.
900 D 900 D 750 D
JUBIL. AUDIT.
LIST. HALL
750 L
MACKENZIE HALL
HENDAY HALL
KELSEY HALL
500 D 400 D 400 D
1500 D 1500 D
GENERAL SERVICES
600 D 300 L
PRINT. SERV.
UTIL. CORR.
500 D
ZONE W
750 D 300 D
STADIUM CAR PARK
2100 L 2100 L 750 L 150 D
CHEM.-MIN. ENGINEER.
WIND. CAR P.
N.-WEST AREA
1500 L
MECHAN. ENGIN.
1500 L 1500 L 1000 L
BIO.-SCIENCES GENETICS
750 D 750 D
EARTH SC.
1000 D 1000 D
PHYSICS
1000 D 1000 D
CHEMISTRY WEST
2250 L 1000 L 1000 L 2250 L
BIO.-SCIENCES BOTANY
SS·16
SS·11
SS·8
SS·3
2000 D 2000 D 2000 D 2000 D 2000 D 1500 L 1500 L 1000 D 1000 D 300 D
SUB.2 HSC SUB.3 HSC SUB.4
CLINICAL SCIENCES
POLIO
UTIL. CORR.
750 D
EDUC. CAR PARK
500 D
ADMIN. BLDG.
1000 D 1000 D
PHYSICAL EDUCATION
1500 L 1500 L
STUDENTS UNION
1500 D
FIELD HOUSE
750 D 750 D 225 D 1500 D 1500 D 1500 D 1500 L 1500 D 500 L
ATHA. HALL
STRU. LAB.
PEMB. HALL
AGRI-FOR. 2 CENTRE
DENTISTRY PHARMACY
CIVIL ELEC.
UTIL. CORR.
750 D
ARTS I
1500 L 1500 L
CHEMISTRY EAST
1500 L
CENTRAL ACADEMIC
750 D
GROWTH CHAMBERS
1500 D
CAMERON LIBRARY
500 D
G.S.A. BLDG.
SS·4
SS·2
SS·1
SS·5

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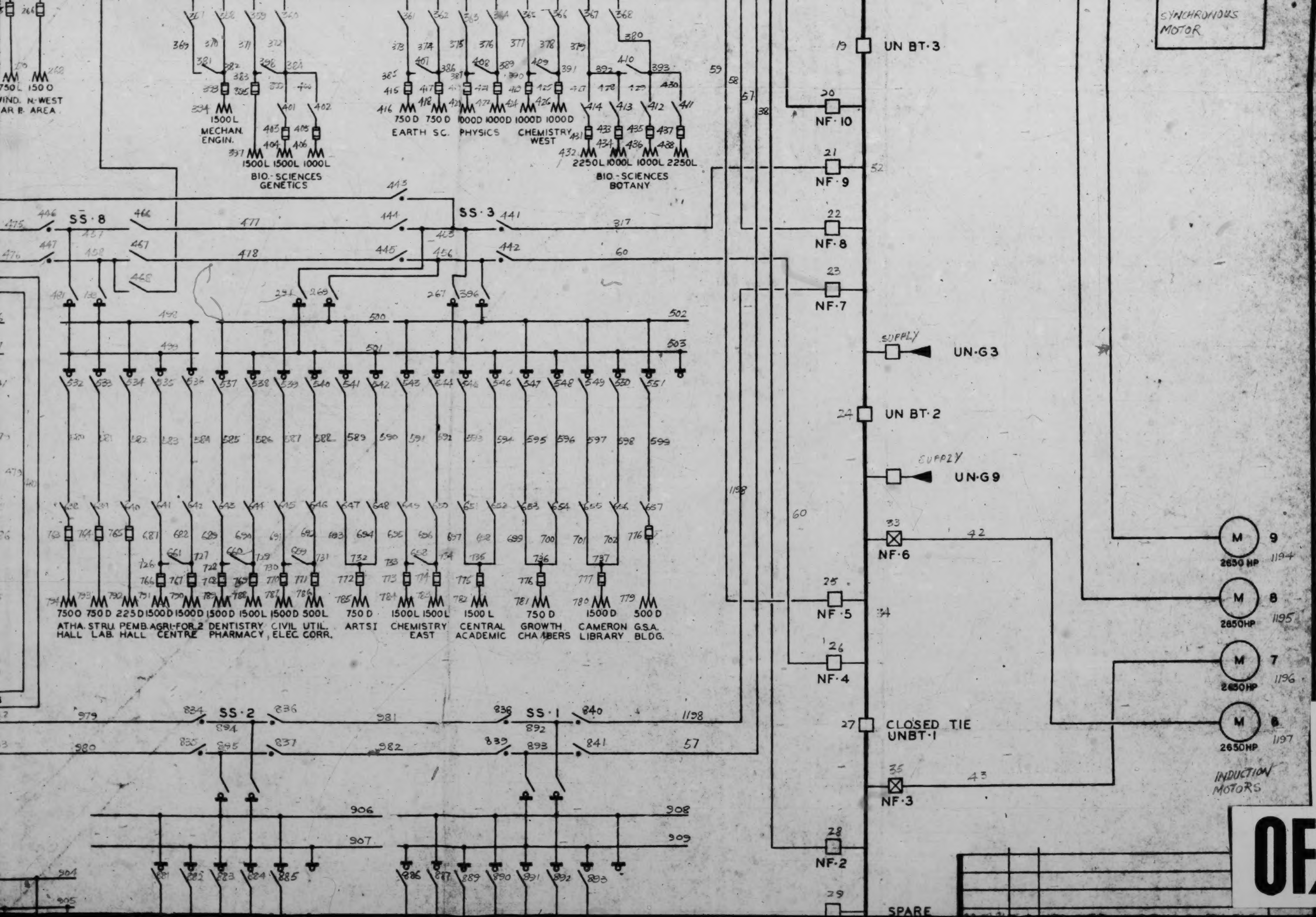

SYNCHRONOUS MOTOR
UN BT·3
NF·10
NF·9
NF·8
NF·7
SUPPLY
UN·G3
UN BT·2
SUPPLY
UN·G9
NF·6
NF·5
NF·4
CLOSED TIE UNBT·1
NF·3
NF·2
SPARE
M 9 2650 HP 1194
M 8 2650HP 1195
M 7 2650HP 1196
M 6 2650HP 1197
INDUCTION MOTORS
SS·8
SS·3
SS·2
SS·1
750L 1500 WIND. N-WEST AR B. AREA
1500L MECHAN. ENGIN.
1500L 1500L 1000L BIO.-SCIENCES GENETICS
750 D 750 D EARTH SC.
1000D 1000D PHYSICS
1000D 1000D CHEMISTRY WEST
2250L 1000L 1000L 2250L BIO.-SCIENCES BOTANY
750O ATHA. HALL
750 D STRU. LAB.
225 D PEMB. HALL
1500 D 1500 D AGRI-FOR.2 CENTRE
1500 D 1500 L DENTISTRY PHARMACY
1500 D 500L CIVIL ELEC. UTIL. CORR.
750 D ARTS I
1500L 1500L CHEMISTRY EAST
1500 L CENTRAL ACADEMIC
750 D GROWTH CHAMBERS
1500 D CAMERON LIBRARY
500 D G.S.A. BLDG.
317
60
477
478
502
503
500
501
498
499
906
907
908
909
979
980
981
982
1198
57
42
43
52
59
58
38

6

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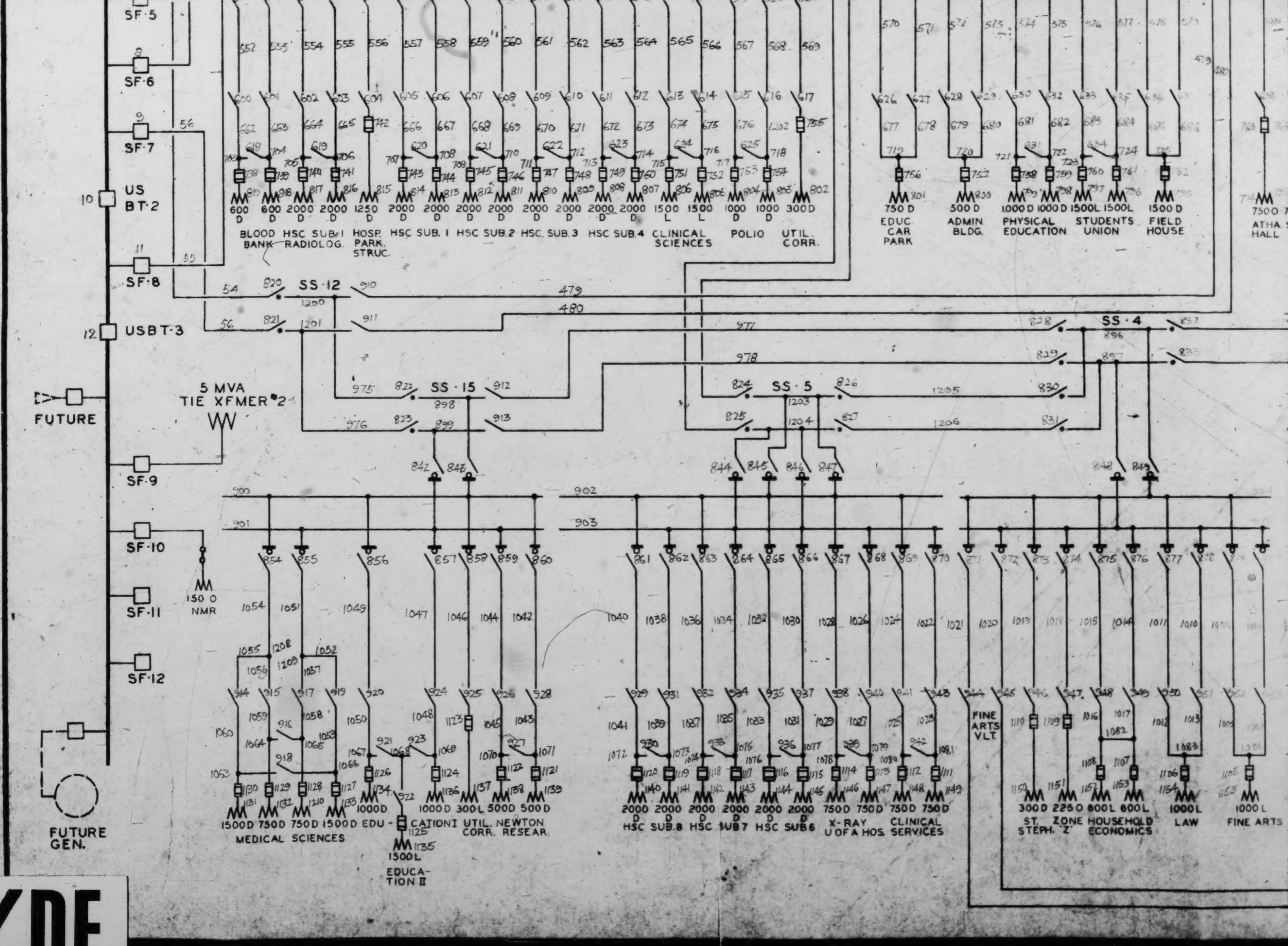
SF·5
SF·6
SF·7
US BT·2
SF·8
USBT·3
FUTURE
5 MVA TIE XFMER #2
SF·9
SF·10
150 0 NMR
SF·11
SF·12
FUTURE GEN.
BLOOD BANK
HSC SUB/I RADIOLOG.
HOSP. PARK. STRUC.
HSC SUB. I
HSC SUB.2
HSC SUB.3
HSC SUB.4
CLINICAL SCIENCES
POLIO
UTIL. CORR.
EDUC CAR PARK
ADMIN. BLDG.
PHYSICAL EDUCATION
STUDENTS UNION
FIELD HOUSE
ATHA. HALL
SS·12
SS·15
SS·5
SS·4
MEDICAL SCIENCES
EDUCATION I
EDUCATION II
UTIL. CORR.
NEWTON RESEAR.
HSC SUB.8
HSC SUB7
HSC SUB6
X-RAY U OF A HOS.
CLINICAL SERVICES
FINE ARTS VLT
ST. STEPH.
ZONE 'Z'
HOUSEHOLD ECONOMICS
LAW
FINE ARTS

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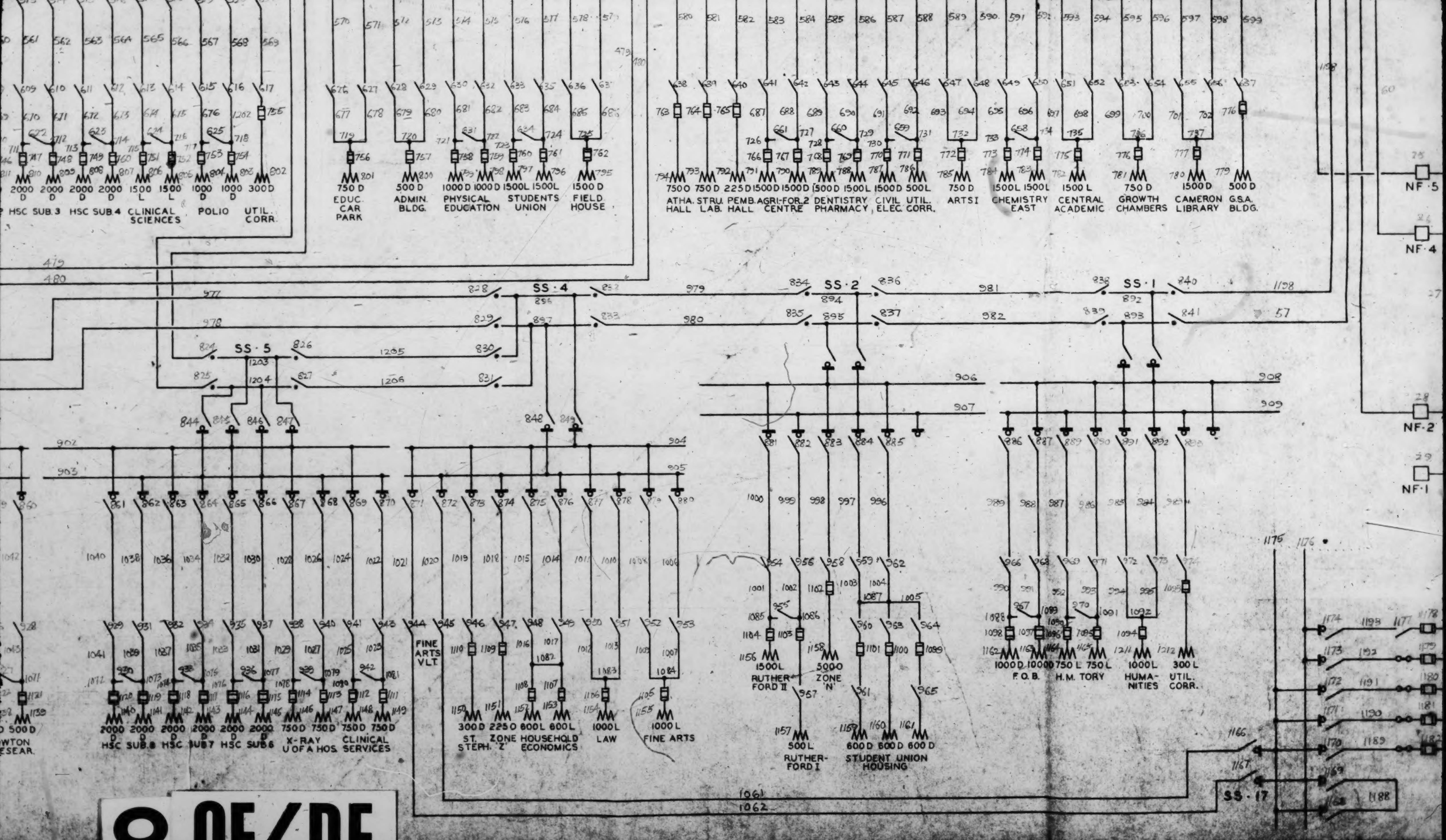

SS·1
SS·2
SS·4
SS·5
SS·17
NF·5
NF·4
NF·2
NF·1
2000 D 2000 D 2000 D 2000 D 1500 L 1500 L 1000 D 1000 D 300 D
HSC SUB.3
HSC SUB.4
CLINICAL SCIENCES
POLIO
UTIL. CORR.
750 D EDUC. CAR PARK
500 D ADMIN. BLDG.
1000 D 1000 D PHYSICAL EDUCATION
1500L 1500L STUDENTS UNION
1500 D FIELD HOUSE
750 D ATHA. HALL
750 D STRU. LAB.
225 D PEMB. HALL
1500 D 1500 D AGRI-FOR. 2 CENTRE
1500 D 1500 L DENTISTRY PHARMACY
1500 D CIVIL ELEC.
500 L UTIL. CORR.
750 D ARTS I
1500 L 1500 L CHEMISTRY EAST
1500 L CENTRAL ACADEMIC
750 D GROWTH CHAMBERS
1500 D CAMERON LIBRARY
500 D G.S.A. BLDG.
500 D NEWTON RESEAR.
2000 D 2000 D HSC SUB.8
2000 D HSC SUB7
2000 D 2000 D HSC SUB6
750 D 750 D X-RAY U OF A HOS.
750 D 750 D CLINICAL SERVICES
FINE ARTS VLT.
300 D ST. STEPH.
225 O ZONE 'Z'
600 L 600 L HOUSEHOLD ECONOMICS
1000 L LAW
1000 L FINE ARTS
1500 L RUTHERFORD II
500 O ZONE 'N'
500 L RUTHERFORD I
600 D 600 D 600 D STUDENT UNION HOUSING
1000 D 1000 D F.O.B.
750 L 750 L H.M. TORY
1000 L HUMANITIES
300 L UTIL. CORR.

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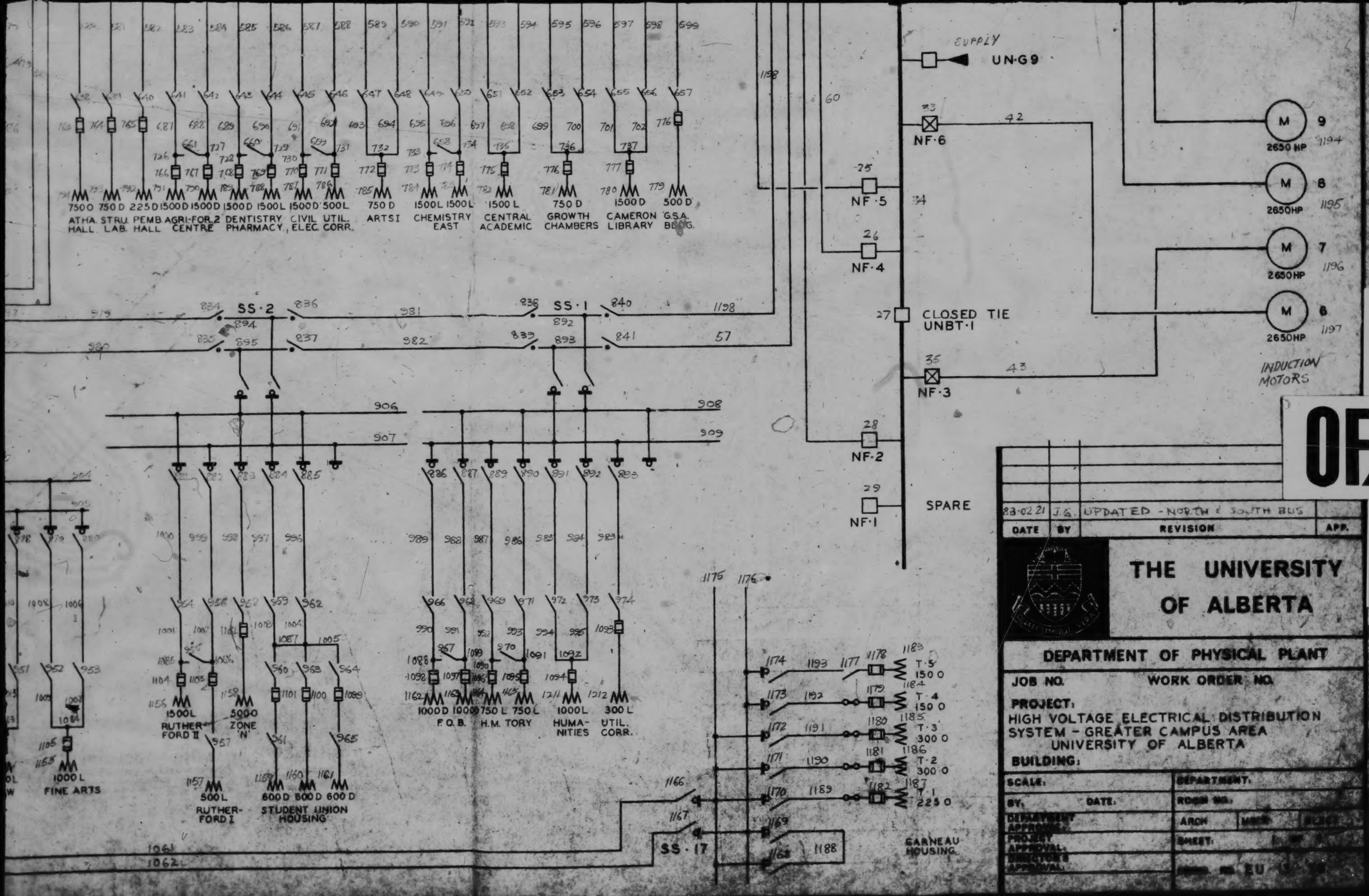
SUPPLY
UN·G9
NF·6
42
NF·5
NF·4
CLOSED TIE
UNBT·1
NF·3
43
NF·2
NF·1
SPARE
M 9 2650 HP 1194
M 8 2650HP 1195
M 7 2650HP 1196
M 6 2650HP 1197
INDUCTION MOTORS
SS·2
SS·1
SS·17
906
907
908
909
1198
57
60
7500 ATHA. HALL
750 D STRU. LAB.
225 D PEMB. HALL
1500 D AGRI-FOR. CENTRE
1500 D
1500 D DENTISTRY PHARMACY
1500 L
1500 D CIVIL ELEC.
500 L UTIL. CORR.
750 D ARTS I
1500 L 1500 L CHEMISTRY EAST
1500 L CENTRAL ACADEMIC
750 D GROWTH CHAMBERS
1500 D CAMERON LIBRARY
500 D G.S.A. BLDG.
1500 L RUTHERFORD II
5000 ZONE 'N'
500 L RUTHERFORD I
600 D 600 D 600 D STUDENT UNION HOUSING
1000 L FINE ARTS
1000 D 1000 D F.O.B.
750 L 750 L H.M. TORY
1000 L HUMANITIES
300 L UTIL. CORR.
T·5 150 0
T·4 150 0
T·3 300 0
T·2 300 0
T·1 225 0
GARNEAU HOUSING
1061
1062

83·02 21	J.G.	UPDATED - NORTH & SOUTH BUS	
DATE	BY	REVISION	APP.

THE UNIVERSITY OF ALBERTA

DEPARTMENT OF PHYSICAL PLANT

JOB NO. **WORK ORDER NO.**

PROJECT:
HIGH VOLTAGE ELECTRICAL DISTRIBUTION
SYSTEM - GREATER CAMPUS AREA
UNIVERSITY OF ALBERTA

BUILDING:

SCALE:	DEPARTMENT:
BY: DATE:	ROOM NO.
DEPARTMENT APPROVAL:	ARCH MECH. ELEC.
PROJECT APPROVAL:	SHEET: [illegible] OF [illegible]
DIRECTOR'S APPROVAL:	DWG. NO. EU [illegible]

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OF/DE

9